

**TECHNICAL SUPPORT DOCUMENT**  
**POTENTIAL RECYCLING OF SCRAP METAL**  
**FROM NUCLEAR FACILITIES**

**PART I: RADIOLOGICAL ASSESSMENT OF**  
**EXPOSED INDIVIDUALS**

**Volume 2: Appendices A-F**

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**APPENDIX A**

**SCRAP METAL INVENTORIES AT U.S. NUCLEAR POWER PLANTS**

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## SCRAP METAL INVENTORIES AT U.S. NUCLEAR POWER PLANTS

### A.1 INTRODUCTION

At the end of 1999 the U.S. commercial nuclear power industry was represented by 104 operating reactors and 27 nuclear power reactors formerly licensed to operate (U.S. NRC 2000). In the next three decades, most of the operating licenses of reactors currently in operation—originally valid for 40 years—will have expired.<sup>1</sup>

With the publication of the NRC's Decommissioning Rule in June 1988 (U.S. NRC 1988), owners and/or operators of licensed nuclear power plants are required to prepare and submit plans and cost estimates for decommissioning their facilities to the NRC for review. Decommissioning, as defined in the rule, means to remove nuclear facilities safely from service and to reduce radioactive contamination to a level that permits release of the property for unrestricted use and termination of the license. The decommissioning rule applies to the site, buildings, and contents and equipment. Currently, several utilities have submitted a decommissioning plan to the NRC for review.

Historically, the NRC has defined three classifications for decommissioning of nuclear facilities:

- **DECON** is defined by the NRC as "the alternative in which the equipment, structures, and portions of a facility and site containing radioactive contaminants are removed or decontaminated to a level that permits the property to be released for unrestricted use shortly after cessation of operations."
- **SAFSTOR** is defined as "the alternative in which the nuclear facility is placed and maintained in a condition that allows the nuclear facility to be safely stored and subsequently decontaminated (deferred dismantlement) to levels that permit release for unrestricted use."

The SAFSTOR decommissioning alternative provides a condition that ensures public health and safety from residual radioactive contamination remaining at the site, without the need for extensive modification to the facility. Systems not required to be operational for fuel storage, maintenance and surveillance purposes during the dormancy period are to be drained, de-energized and secured.

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<sup>1</sup> As stated in Chapter 2, the NRC has issued a rule allowing a licensee to apply for a 20-year renewal of its original operating license. To date, five reactors have been granted such license renewals, a number of other renewal applications are pending, and more applications are anticipated.

- **ENTOMB** is defined as "the alternative in which radioactive contaminants are encased in a structurally long-lived material, such as concrete; the entombed structure is appropriately maintained and continued surveillance is carried out until the radioactive material decays to a level permitting unrestricted release of the property."

Over the years, the basic concept of the three alternatives has remained unchanged. However, because of the accumulated inventory of spent nuclear fuel (SNF) in the reactor storage pool and the requirement for about seven years of pool storage for the SNF before transfer to dry storage, the timing and steps in the process for each alternative have had to be adjusted to reflect present conditions. For the DECON alternative, it is assumed that the owner has a strong incentive to decontaminate and dismantle the retired reactor facility as promptly as possible, thus necessitating transfer of the stored SNF from the pool to a dry storage facility on the reactor site. While continued storage of SNF in the pool is acceptable, the 10 CFR Part 50 license could not be terminated until the pool had been emptied, and only limited amounts of decontamination and dismantlement of the facility would be required. This option also assumes that an acceptable dry transfer system will be available to remove the SNF from the dry storage facility and to place it into licensed transport casks when the time comes for DOE to accept the SNF for disposal at a high level waste repository.

In addition, the amended regulation stipulates that alternatives, which significantly delay completion of decommissioning, such as use of a storage period, will be acceptable if sufficient benefit results. The Commission indicated that a storage period of up to 50 years and a total of 60 years between shutdown and decommissioning is a reasonable option for decommissioning a light water reactor. In selecting 60 years as an acceptable period of time for decommissioning of a nuclear power reactor, the Commission considered the amount of radioactive decay likely to occur during an approximately 50-year storage period and the time required to dismantle the facility.

In summary, the reactor facility will need to adequately cool the high-burnup assemblies from the final fuel core in the pool for up to seven years and must fulfill the regulatory requirements that critical support systems be maintained in operable conditions. Therefore, the time between shutdown, decontamination and the earliest date of dismantling efforts that would generate scrap metal is likely to be about 10 years. This interval may extend up to 60 years under the SAFSTOR decommissioning alternative. A longer time interval has the obvious benefit of greatly reducing radionuclide inventories through radioactive decay. However, a simple inverse

correlation between reduced levels of contamination and increased quantities of scrap metal with a potential for clearance cannot be inferred. It is likely that for most scrap metal, the longer decay time may merely affect the choice of decontamination method and/or decontamination effort required to meet a desired standard. For example, a storage period that reduces beta/gamma surface contamination of  $10^7$  dpm/100 cm<sup>2</sup> at 10 years post-shutdown to  $10^5$  dpm/100 cm<sup>2</sup> (i.e., a 100-fold reduction) would still require substantial decontamination in order to meet current standards defined by NRC Regulatory Guide 1.86 (U.S. AEC 1974). However, since the reduced activity would most likely be dominated by Cs-137, the method and level of effort required for successful decontamination would be different than that employed at an earlier time.

The potential for clearance of scrap metal is, therefore, dictated by the cost-effectiveness with which materials can be decontaminated to acceptable levels. Estimates of scrap metal quantities must consider starting levels of contamination and whether the contamination is surficial or volumetrically distributed.

Residual radioactive contaminants of reactor components/systems and building structures is generally grouped as: (1) activation products that are distributed volumetrically, (2) activation and fission products in the form of corrosion films deposited on internal surfaces, and (3) contamination of external surfaces that result from the deposition of liquid and airborne radioactive materials associated with steam, reactor coolant and radioactive waste streams.

Most of the scrap metal generated by the complete dismantling of a nuclear power plant is not expected to be radioactive. The non-radioactive scrap includes the large quantities of structural metals and support systems that have *not* been exposed to radioactivity during reactor operations. Conversely, some metal components will undoubtedly be so contaminated as to render them unsuitable for clearance.

## A.2 CHARACTERISTICS OF REFERENCE REACTOR FACILITIES

A crucial factor affecting the quantity of metal and associated contamination levels is the basic design of the reactor. Each of the nuclear power reactors currently operating in the U.S. is either a pressurized water reactor (PWR) or a boiling water reactor (BWR). Of the 104 operating reactors, 35 are BWRs manufactured by General Electric and 69 are PWRs manufactured by Westinghouse, Combustion Engineering and Babcock and Wilcox (U.S. NRC 2000).

Appendix A-1 provides a complete listing of U.S. nuclear power reactors along with demographic data that includes projected year of shutdown.

In the 1976-1980 time frame, two studies were carried out for the NRC by the Pacific Northwest Laboratory (PNL) that examined the technology, safety and costs of decommissioning large reference nuclear power plants. Those studies—"Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," NUREG/CR-0130 (Smith et al. 1978) and "Technology, Safety and Costs of Decommissioning a Reference Boiling Water Reactor Power Station," NUREG/CR-0672 (Oak et al. 1980)—reflected the industrial and regulatory situation of the time.

To support the final Decommissioning Rule issued in 1988, the earlier PNL studies were updated with the issuance of "Revised Analyses of Decommissioning for the Reference Pressurized Water Reactor Station," NUREG/CR-5884 (Konzek et al. 1995) and "Revised Analyses of Decommissioning for the Reference Boiling Water Reactor Power Station," NUREG/CR-6174 (Smith et al. 1996). The four NUREG reports cited above, along with several other NRC reports and selected decommissioning plans on file with the Commission, represent the primary source of information used to characterize Reference PWR and BWR facilities and to derive estimates of scrap metal inventories for the industry at large.

#### A.2.1 Reference PWR Design and Building Structures

The Reference PWR facility is the 3,500 MWt (1,175 MWe) Trojan Nuclear Plant (TNP) at Rainier, Oregon, operated by the Portland General Electric Company (PGE). Designed by Westinghouse, this reactor is considered a typical PWR that has been cited as the Reference PWR (Smith et al. 1978; Konzek et al. 1995).

The NRC granted the operating license for the TNP on November 21, 1975, and the plant formally began commercial operation on March 20, 1976. TNP's operating license was scheduled to expire on February 8, 2011. However, on November 9, 1992, the TNP was shut down when a leak in the "B" steam generator was detected and the licensee notified the NRC of its decision to permanently cease operations in January 1993. Following the transfer of spent fuel from the reactor vessel to the spent fuel pool in May of 1993, TNP's operating license was reduced to a possession only license. TNP's 17-year operating period encompassed 14 fuel cycles and approximately 3,300 effective full-power days. In the decommissioning plan

submitted by PGE, the licensee has proposed the DECON approach with a five-year delay period prior to decontamination and dismantlement (Portland General Electric 1996).

In a PWR, the primary coolant is heated by the nuclear fuel core but is prevented from boiling by a pressurizer, which maintains a pressure of about 2,000 psi. The principal systems and components of the nuclear steam supply system are illustrated in Figure A-1. Components of interest are the reactor vessel, which contains the fuel and coolant, and the reactor coolant system (RCS). The reactor vessel also contains internal support structures (not shown) that constrain the fuel assemblies, direct coolant flow, guide in-core instrumentation and provide some neutron shielding. The RCS consists of four loops for transferring heat from the reactor's primary coolant to the secondary coolant system. Each loop consists of a steam generator, a reactor coolant pump and connecting piping. Steam generated from secondary feedwater is passed through the turbine, condensed back to water by the condenser and recycled.

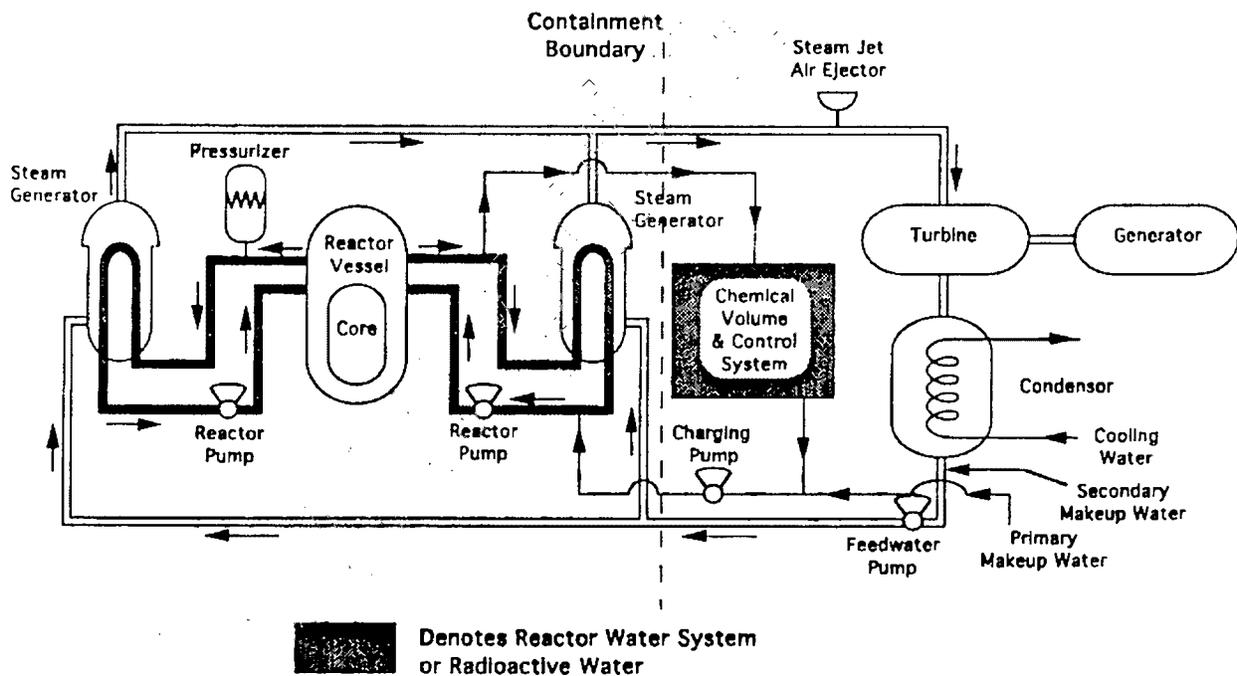


Figure A-1. Pressurized Water Reactor (Dyer 1994)

Also included in the primary loop is a small side-stream of water that is directed to the chemical volume and control system (CVCS). The CVCS provides chemical and radioactive cleanup of the primary coolant through demineralizers and evaporators. The primary coolant is reduced in

both pressure and temperature by the CVCS before being processed; therefore, the CVCS is often referred to as the letdown system. The water processed through the CVCS is returned to the primary loops by the charging pumps. Note that the primary coolant processed through the CVCS is brought through the containment boundary or out of the containment building, but the primary coolant providing the heat transfer to the steam generators does not pass through the containment boundary.

As shown in Figure A-1, highly contaminated components of a PWR are those associated with the primary coolant system. Low-level contamination of the secondary loop is a result of steam generator tube leakage in which limited quantities of primary coolant are introduced into the recirculating steam/water. Other major contaminated systems of PWRs not shown in Figure A-1 include the radioactive waste handling system and the spent fuel storage system.

The principal structures requiring decontamination for license termination at the Reference PWR are the (1) reactor building, (2) fuel building and (3) auxiliary building. In addition to housing major plant systems, all three buildings contain contaminated systems and substantial quantities of contaminated structural metals that are candidates for clearance.

#### A.2.1.1 Reactor Building

The reactor building houses the nuclear steam supply system. Since its primary purpose is to provide a leak-tight enclosure under normal as well as accident conditions, it is frequently referred to as the containment building. Major interior structures include the biological shield, pressurizer cubicles and a steel-lined refueling cavity. Supports for equipment, operating decks, access stairways, grates and platforms are also part of the containment structure internals.

The reactor building is in the shape of a right circular cylinder, approximately 64 m tall and 22.5 m in diameter. It has a hemispherical dome, a flat base slab with a central cavity and an instrumentation tunnel.

#### A.2.1.2 Fuel Building

The fuel building—approximately 27 m tall, 54 m long, and 19 m wide—is a steel and reinforced concrete structure with four floors. This building contains the spent-fuel storage pool and its cooling system, much of the CVCS, and the solid radioactive waste handling equipment. Major steel structural components include fuel storage racks and liner, support structures for fuel

handling, and components, ducts and piping associated with air conditioning, heating, cooling and ventilation.

#### A.2.1.3 Auxiliary Building

The auxiliary building—approximately 30 m tall, 35 m long and 19 m wide—is a steel and reinforced concrete structure with two floors below grade and four floors above grade. Principal systems contained in the auxiliary building include the liquid radioactive waste treatment systems, filter and ion exchanger vaults, waste gas treatment system, and the ventilation equipment for the containment, fuel and auxiliary buildings.

#### A.2.1.4 Control and Turbine Buildings

Other major building structures with substantial metal inventories include the control building and the turbine building. The principal contents of the control building are the reactor control room, and process and personnel facilities. The principal systems contained in the turbine building are the turbine generator, condensers, associated power production equipment, steam generator auxiliary pumps, and emergency diesel generator units.

Barring major system failures (e.g., steam generator failure) most scrap metal derived from these systems can be assumed to be free of contamination and can, therefore, be excluded from the inventories of scrap metal which are candidates for clearance.

### A.2.2 Reference BWR Design and Building Structures

The 3,320 MWt (1,155 MWe) Washington Public Power Supply System (WPPSS) Nuclear Project No. 2 located near Richland, Wash., is the basis for the Reference BWR facility (Oak et al. 1980; Smith et al. 1996).

The design of a BWR (see Figure A-2) is simpler than a PWR inasmuch as the reactor coolant water is maintained near atmospheric pressure and boiled to generate steam. This allows the coolant to directly drive the turbine. Thereafter, the steam is cooled in the condenser and returned to the reactor vessel to repeat the cycle. In a BWR, the contaminated reactor coolant comes in contact with most major reactor components, including the reactor vessel and piping, steam turbine, steam condenser, feedwater system, reactor coolant cleanup system and steam jet

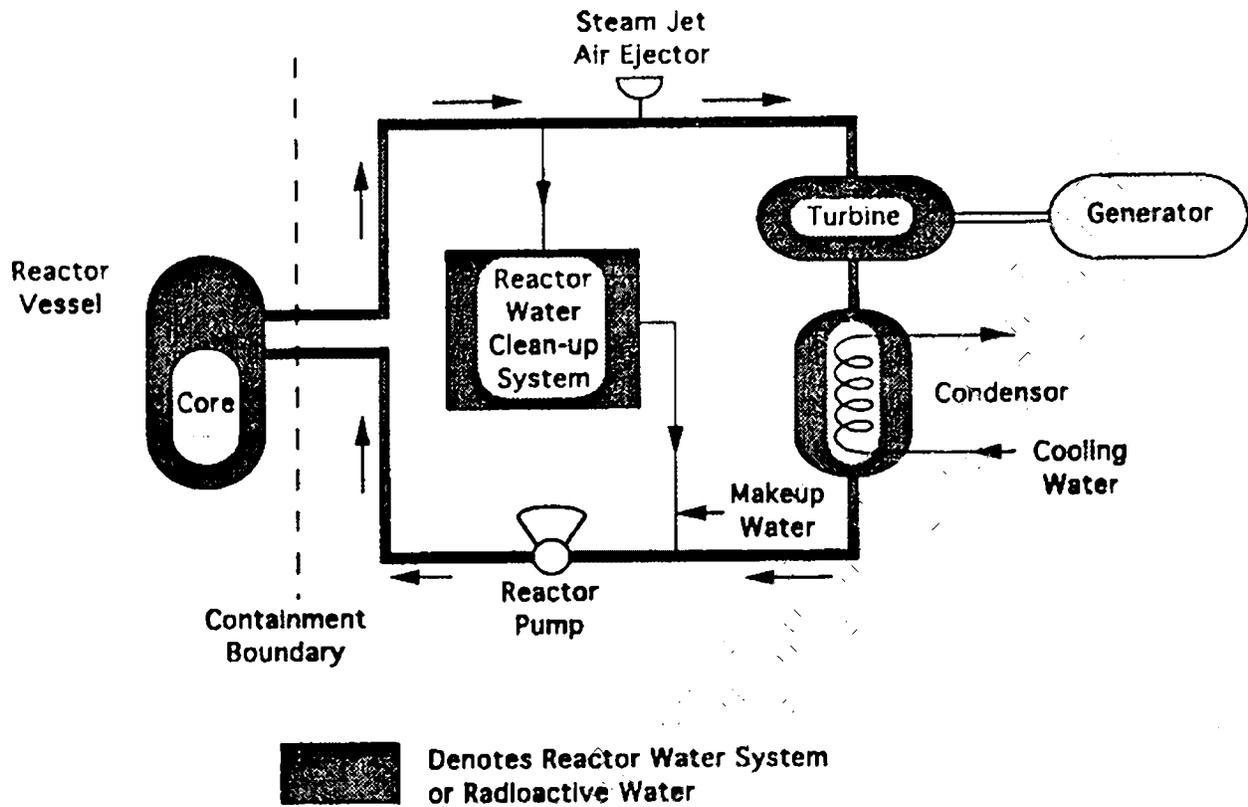


Figure A-2. Boiling Water Reactor (Dyer 1994)

air ejector system. As with the PWR, other major contaminated systems include the radioactive waste treatment system and spent fuel storage system.

The principal buildings requiring decontamination and dismantlement in order to obtain license termination at the reference BWR power station are the reactor building, the turbine generator building, and the radwaste and control building. These three buildings contain essentially all of the activated or radioactively contaminated material and equipment within the plant.

#### A.2.2.1 Reactor Building

The reactor building contains the nuclear steam supply system and its supporting systems. It is constructed of reinforced concrete capped by metal siding and roofing supported by structural steel. The building surrounds the primary containment vessel, which is a free-standing steel pressure vessel. The exterior dimensions of the Reactor Building are approximately 42 m by 53 m in plan, 70 m above grade and 10.6 m below grade to the bottom of the foundation.

### A.2.2.2 Turbine Building

The turbine building, which contains the power conversion system equipment and supporting systems, is constructed of reinforced concrete capped by steel-supported metal siding and roofing. This structure is approximately 60 m by 90 m in plan and 42.5 m high.

### A.2.2.3 Radwaste and Control Building

The radwaste and control building houses, among other systems: the condenser off-gas treatment system, the radioactive liquid and solid waste systems, the condensate demineralizer system, the reactor coolant cleanup demineralizer system and the fuel-pool cooling and cleanup demineralizer system. The building is constructed of reinforced concrete, structural steel, and metal siding and roofing. This structure is approximately 64 by 49 m in plan, 32 m in overall height, and stands as two full floors and one partial floor above the ground floor.

## A.3 RESIDUAL ACTIVITIES IN REFERENCE REACTOR FACILITIES

Significant levels of contamination remain in a nuclear power station following reactor shutdown, even after all spent nuclear fuel has been removed. Neutron-activated structural materials in and around the reactor pressure vessel contain most of the residual activity in a relatively immobile condition. Other sources of radioactive contamination comprise activated corrosion products and fission products leaked from failed fuel, which are transported throughout the station by the reactor coolant streams. The origin and mobility of radioactive contaminants following reactor shutdown leads to grouping of residual activities into five categories of different binding matrices. These categories include:

1. **Activated Stainless Steel.** Reactor internals, composed of Type 304 stainless steel, become activated by neutrons from the core. Radionuclides have very high specific activities and are immobilized inside the corrosion-resistant metal.
2. **Activated Carbon Steel.** Reactor pressure vessels are made of SA533 carbon steel that becomes activated by neutron bombardment. The specific activities are considerably lower than in the stainless steel internals, and the binding matrix is much less corrosion resistant.
3. **Activated Structural Steel, Steel Rebar and Concrete.** In the reactor cavity, these components become activated by neutrons escaping from the reactor vessel. Significant

activation occurs along approximately 15 feet of the reactor cavity vertically centered on the reactor core and to a depth of about 16 inches in the concrete.

4. **Contaminated Internal Surfaces of Piping and Equipment.** Activated corrosion and fission products travel through the radioactive liquid systems in the plant. A portion forms a hard metallic oxide scale on the inside surfaces of pipes and equipment.
5. **Contaminated External Surfaces.** External surfaces may become contaminated over the lifetime of the plant, primarily from leaks, spills and airborne migration of radionuclides contained in the reactor coolant water (RCW). The specific activity of RCW is low, but the contamination is easily mobilized and may be widespread.

All of the neutron-activated metals/materials are contained in the reactor pressure vessel, vessel internals, and structural components inside and within the concrete biological shield.

Total quantities and the relative radionuclide composition of the residual activity are not only affected by reactor design (BWR vs. PWR) but are also strongly influenced by numerous other factors including (1) fuel integrity, (2) rated generating capacity and total years of operation, (3) composition of metal alloys in reactor components and the RCS, (4) coolant chemistry and water control measures, and (5) the performance and/or failures of critical systems and their maintenance over the initial 40-year span of the operating license (see footnote on page A-1).

Table A-1 provides summary estimates of typical residual activities for each of the five major source categories. Inspection of the data reveals that the volumetrically activated stainless steel represents the overwhelming majority of the residual activities. Much smaller activities are found in volumetrically activated carbon steel and internal and external surface contamination consisting of activation and fission products. A more detailed discussion of residual activity by source category is given below.

#### A.3.1 Neutron-Activated Reactor Components and Structural Materials

Contamination of reactor components and structural materials by neutron activation is the result of normal reactor operation. The interaction of neutrons with constituents of stainless steel, carbon steel and concrete in and around the reactor vessel results in high in-situ activities. The radionuclide inventories include significant activities of Cr-51, Mn-54, Fe-55, Fe-59, Co-58, Ni-59 and Ni-63. The specific activities of various radionuclides in materials exposed to a neutron flux is highly variable and depends upon (1) the concentration of the parent nuclide and its

neutron cross-section, (2) the radioactive half-life of the radionuclide, (3) the neutron flux intensity at the given location, and (4) the duration of neutron exposure.

Table A-1. Sources of Residual Activities in Reference BWR and PWR

Source	Residual Activity (Ci)	
	BWR <sup>a</sup>	PWR <sup>b</sup>
Activated Stainless Steel	6.6e+06	4.8e+06
Activated Carbon Steel	2.9e+03	2.4e+03
Activated Structural Components, Rebar, Metal Plates, I-Beams	1.2e+03	1.2e+03
Internal Surface Contamination of Piping and Equipment	8.5e+03	4.8e+03
External Contamination of Equipment, Floors, Walls, Other Surfaces	1.1e+02	1.1e+02 <sup>c</sup>

<sup>a</sup> Oak et al. 1980

<sup>b</sup> Smith et al. 1978

<sup>c</sup> Implied value (U.S. NRC 1994)

#### A.3.1.1 Reference BWR

The average activity concentrations and estimated total activities for Reference BWR structural components with significant amounts of neutron activation are listed in Table A-2.

The Reference BWR reactor vessel is fabricated of SA533 carbon steel about 171 mm thick and is clad internally with 3 mm of Type 304 stainless steel. The total mass of the empty vessel is about 750 metric tons (t). The major internal components include the fuel core support structure; steam separators and dryers; coolant recirculation jet pumps; control rod guide tubes; distribution piping for feedwater, core sprays and liquid control; in-core instrumentation, and miscellaneous other components. Collectively, these internals, made of stainless steel, represent about 250 t.

#### A.3.1.2 Reference PWR

The right circular cylinder of the Reference PWR is constructed of carbon steel about 216 mm in thickness and is clad on the inside with stainless steel or Inconel having a thickness of about 4 mm. The approximate dimensions of the vessel are 12.6 m high and 4.6 m in outer diameter. The vessel weighs about 400 t.

Table A-2. Estimated Activities of Neutron-Activated Reactor Components in a BWR

Component (number)	Average Activity Concentration (Ci/m <sup>3</sup> )	Total Activity (Ci)
Core Shroud (1)	1.68e+06	6.30e+06
Jet Pump Assembly (10)	2.62e+04	2.00e+03
Reactor Vessel (1)		2.16e+03
Cladding	1.07e+03	
Shell Wall	1.12e+02	
Steam Separator Assembly (1)		9.60e+03
Shroud Head Plant	1.03e+04	
Steam Separator Risers	2.53e+03	
Top Fuel Guide (1)	9.71e+04	3.01e+04
Orificed Fuel Support (193)	1.01e+03	7.01e+02
Core Support Plate (1)	2.56e+02	6.50e+02
Incore Instrument Strings (55)	7.67e+05	1.10e+04
Control Rod (185)	5.11e+05	1.78e+05
Control Rod Guide Tube (185)	2.16e+02	9.47e+01
Total		6.55e+06

Source: Oak et al. 1980

The vessel's internal structures support and constrain the fuel assemblies, direct coolant flow, guide in-core instrumentation and provide some neutron shielding. The principal components are: the lower core support assembly, which includes the core barrel and shroud, with neutron shield pads, and the lower core plate and supporting structure; and the upper core support and in-core instrumentation support assemblies. These structures are made of 304 stainless steel and have a total mass of about 190 t.

Based on 40 years of facility operation and assuming 30 effective full-power years (EFPY) of reactor operation, the total activity contained in the activated vessel and internals is estimated to be 4.8 million curies (see Table A-3). Extra-vessel materials subject to significant neutron activation ( $\approx 10$  curies) includes the reactor cavity steel liner and a limited quantity of reinforcement steel (rebar). Additionally, the concrete bioshield contains an estimated total inventory of about 1,200 curies.

Table A-3. Neutron-Activated Reactor Components in a PWR

Component	Average Activity Concentration (Ci/m <sup>3</sup> )	Total Activity (Ci)
Shroud	2.97e+06	3.43e+06
Lower 4.7 m of core barrel	3.07e+05	6.52e+05
Thermal shield	1.45e+05	1.46e+05
Vessel inner cladding	7.73e+03	1.50e+03
Lower 5.02 m of vessel wall	9.04e+02	1.76e+04
Upper grid plate	4.20e+04	2.43e+04
Lower grid plate	1.12e+06	5.53e+05
Total		4.82e+06

Source: Smith et al 1978

The projected estimates of Table A-3 for the Reference PWR (i.e., Trojan Nuclear Plant) made in 1978 can be compared to the more current estimates contained in that plant's decommissioning plan (submitted to the NRC in 1996). Table A-4 identifies revised calculated inventories of activation products for 1993, or one year after shutdown. The recalculated value of about 4.2 million curies is about 13% lower than the original estimate of 4.8 million curies and principally reflects the difference between 17 years of actual plant operation and the initial projection of 40 years.

Table A-4. Activation Levels at Trojan Nuclear Plant One Year after Shutdown

System	Activity (Ci)
Reactor Vessel	6.20e+03
Reactor Vessel Internals	4.16e+06
Vessel Clad and Insulation	2.37e+04
Bioshield Wall	8.30e+02
Total	4.19e+06

The considerably higher activities calculated for a Reference BWR primarily reflect the larger size and mass of the vessel and its internals.

For both PWR and BWR plants, the range of activity concentrations among individual reactor components at time of shutdown is likely to vary over several orders of magnitude. Nevertheless, even those components with the lowest activity concentrations would still have residual activities far in excess of any conceivable levels that would permit clearance. (Note: at a specific gravity of 7.86, a cubic meter of steel containing one curie has a specific activity of 0.13  $\mu\text{Ci/g}$ .) Furthermore, these components also exhibit high levels of interior surface contamination. While surface contamination is potentially removable, the volumetrically distributed activation products are not.

For this reason, the reactor vessel and all internal components identified in Tables A-2 and A-3 must be excluded from plant material inventories which are potential candidates for clearance. Excluded for similar reasons are certain metal components used for structural support and reinforcement (i.e., rebar, I-beams, and floor and reactor cavity liner plates) that exhibit significant levels of activation products.

Scrap metal that can potentially be cleared can therefore originate only in reactor systems and structural components where contamination is limited to interior and exterior surfaces.

### A.3.2 Internal Surface Contamination of Equipment and Piping

Activated corrosion products from structural materials in contact with the reactor coolant and fission products from leaking fuel contribute to the radioactive contamination of reactor coolant streams during plant operation. Although most of these contaminants are removed through filtration and demineralization by the CVCS, a small portion remains in the coolant. With time, some of the contaminants, principally the neutron-activated, insoluble corrosion products, tend to deposit on inner surfaces of equipment and piping systems. The resulting metal oxide layer consists primarily of iron, chromium and nickel with smaller, but radiologically significant, quantities of cobalt, manganese and zinc. This section characterizes the mixture of internal surface contaminants and their relative distribution within major components associated with BWR and PWR power plants.

#### A.3.2.1 Measurements of Internal Surface Contamination at Six Nuclear Power Plants

In a 1986 PNL study, six nuclear power plants—three PWRs and three BWRs—were assessed for residual inventories and distributions of long-lived radionuclides following plant shutdown (Abel et al. 1986). Residual concentrations in the various plant systems decreased in the

following order: (1) primary coolant loop, (2) radwaste handling system, and (3) secondary coolant loop in PWRs and condensate system in BWRs. Table A-5 lists total estimated activities at the six plants, as well as the electrical ratings and the approximate number of operational years of the plants at the time of the assessments. The operational periods ranged from 8.3 years for Turkey Point Unit 3 to slightly over 18 years for Dresden Unit 1.

Table A-5. Residual Activities and Operating Parameters of Six Nuclear Power Plants<sup>2</sup>

Stations	Total Inventory (Ci)	Period of Operation (y)	Power Rating (MWe)	Reactor Type
Humboldt Bay	600	13	63	BWR
Dresden-1	2,350	18.3	210	BWR
Monticello	514	10	550	BWR
Indian Point-1	1,050	11	170	PWR
Turkey Point-3	2,580	8.3	660	PWR
Rancho Seco	4,470	8.8	935	PWR

Source: Abel et al. 1986

<sup>2</sup> Total inventory includes radionuclides with half-lives greater than 245 days (i.e., Zn-65). Inventories in activated metal components of the reactor pressure vessel and internals and activated concrete are excluded.

The relative radionuclide composition of internally contaminated surfaces at the six plants also showed considerable variation (see Table A-6). Fluctuations in compositions were due to numerous factors including: (1) the elapsed time since reactor shutdown; (2) rated generating capacity; (3) materials of construction of the operating systems; (4) reactor type (PWR or BWR); (5) coolant chemistry and corrosion control; (6) fuel integrity during operations; and (7) episodic equipment failure and leakage of contaminated liquids.

Inventories include only the radioactive contamination of corrosion film and crud<sup>2</sup> on surfaces of the various plant systems, and do not include the highly activated components of the pressure vessel. The most abundant radionuclides in samples two to three months old included Mn-54, Fe-55, Co-58, Co-60 and Ni-63. Zinc-65 was present in relatively high concentrations in BWR corrosion film samples. However, Fe-55, and Co-57+Co-60 were the most abundant radionuclides at all stations except Monticello. These radionuclides constituted over 95% of the

<sup>2</sup> A colloquial term for corrosion and wear products (rust particles, etc.) that become radioactive (i.e., activated) when exposed to radiation. The term is actually an acronym for Chalk River Unidentified Deposits, the Canadian plant at which the activated deposits were first discovered.

estimated inventories at Humboldt Bay and Turkey Point. At Indian Point-1, Dresden-1, Turkey Point-3 and Rancho Seco, they accounted for 82, 74, 98 and 70%, respectively, of the total estimated inventory. Although Fe-55 and Co-60 accounted for the majority of the inventory (greater than 60% at five of the six stations), the relationship between the two radionuclides was quite variable. The transuranic nuclides (Pu-238, Pu-239, Pu-240, Am-241, Cm-242 and Cm-244) constituted varying percentages of the total inventory, ranging from 0.001% at Rancho Seco to 0.1% at Dresden-1.

Table A-6. Relative Activities of Long-Lived Radionuclides at Six Nuclear Power Plants<sup>†</sup>

Radionuclide	Relative Activity, Decay-Corrected to Shutdown Date (%) <sup>*</sup>					
	BWRs			PWRs		
	Humboldt Bay	Dresden-1	Monticello	Indian Point-1	Turkey Point-3	Rancho Seco
Mn-54	3	0.9	1	4	0.4	4
Fe-55	90	28	1	67	31	28
Co-57	—	—	—	—	43	24
Co-60	6	46	11	15	24	18
Ni-59	—	0.09	—	0.02	4e-03	0.1
Ni-63	0.2	5	0.04	2	0.1	19
Zn-65	—	19	84	11	1	0.09
Sr-90	4e-03	7e-03	2e-03	7e-04	8e-04	< 0.01
Nb-94	< 4e-03	< 3e-03	< 0.1	8e-04	< 4e-03	< 4e-03
Tc-99	3e-04	4e-05	8e-05	8e-05	8e-03	< 5e-03
Ag-110m	—	—	—	—	—	4
I-129	< 3e-06	< 1e-05	< 1e-06	2e-05	< 3e-03	< 1e-05
Cs-137	0.5	0.04	2	0.5	—	0.4
Ce-144	—	1	—	—	0.2	< 0.04
TRU <sup>**</sup>	5e-03	0.1	8e-03	2e-03	6e-03	1e-03
Total (Ci)	596	2,350	448	1,070	2,580	4,460

Source: Abel et al. 1986

<sup>†</sup> Excludes activated metal components of the reactor pressure vessel and internals and activated concrete

<sup>\*</sup> Relative activity of each nuclide as a percentage of total activity at each power plant

<sup>\*\*</sup> Transuranic alpha-emitting radionuclides with half-lives greater than 5 years, including Pu-238, Pu-239, Pu-240, Am-241, Am-243 and Cm-244

Secondary coolant loops in PWRs and condensate systems in BWRs contained much lower activity concentrations than observed in primary loop or feedwater samples. Typically, concentrations were two or more orders of magnitude lower in secondary system samples.

As expected, the steam generators contained the single largest repository of internally deposited radionuclides at the PWR stations examined (see Table A-7). The percentages of the total residual radionuclide inventories in the steam generators were 77, 89 and 94% for Indian Point-1, Turkey Point-3 and Rancho Seco, respectively. The other repository of significance in a PWR is the radwaste system, which typically contained 5 to 10% of the total residual inventory.

Table A-7. Distribution of Activities in Major Systems of Three PWRs (%)

System	Turkey Point-2	Indian Point-1	Rancho Seco	Average
Steam Generators	89	77	94	86.7
Pressurizer	0.5	0.5	0.33	0.4
RCS Piping	0.9	2.6	0.71	1.4
Piping (Except RCS)	< 0.01	14	< 0.01	4.7
Secondary Systems	0.1	0.2	0.05	0.1
Radwaste	9.2	7	5	7.1

Source: Abel et al. 1986

#### A.3.2.2 Internal Surface Contamination Levels Reported in Decommissioning Plans

A small number of commercial nuclear power facilities, which have experienced a premature shutdown or have projected shutdown within the next few years, have submitted a decommissioning plan to the NRC for review. Summarized below are system-specific internal contamination levels reported for one BWR and two PWRs.

##### **Big Rock Point Nuclear Plant**

The Big Rock Point Nuclear Plant is a small (67 MWe) BWR designed by the General Electric Company and constructed by Bechtel Power Corporation. Owned and operated by Consumers Power Company, the plant started commercial operation in March 1963 and was shut down in August 1997. Table A-8 presents summary data of systems internally contaminated (Consumers Power, 1995).

Table A-8. Internal Contamination Levels of Big Point Nuclear Plant at Shutdown

System	Surface Contamination Level (dpm/100 cm <sup>2</sup> )
Liquid Rad Waste Tanks	3e+10
Nuclear Steam Supply	9e+09
RDS	3e+09
Main Steam System	4e+08
Fuel Pool	4e+08
Liquid Radwaste System	4e+08
Condensate System	5e+07
Resin Transfer System	3e+07
Off-gas System	3e+07
Control Rod Drive	6e+06
Rad Waste Storage	9e+05
Fuel Handling Equip	7e+05
Heating & Cooling System	3e+05

**San Onofre Nuclear Generation Station Unit 1 (SONGS 1)**

SONGS 1 is a 436-MWe PWR that started operation in 1968. As a result of an agreement with the California Public Utility Commission, operation of SONGS 1 was permanently discontinued on November 30, 1992 at the end of fuel cycle #11. A preliminary decommissioning plan, submitted to the NRC on December 1, 1992, proposed to maintain SONGS 1 in safe storage until the permanent shutdown of SONGS 2 and 3. SONGS 2 and 3 are licensed to operate until 2013.

In support of the SONGS 1 decommissioning plan, scoping surveys and analyses were performed that supplemented an existing radiological data base (Southern California Edison 1994). The containment building, fuel storage building and radwaste/auxiliary building were identified as the principal structures containing significant levels of radioactivity within plant systems. Systems were grouped by contamination levels defined as (1) highly contaminated, (2) medium-level contaminated and (3) low-level contaminated. Based on total radionuclide inventories and surface areas, an average contamination level for each of the three groupings was derived (see Table A-9).

Table A-9. Plant Systems Radioactivity Levels at SONGS I

Plant Systems	Total Area (cm <sup>2</sup> )	Surface Contamination Level (dpm/100 cm <sup>2</sup> )	Total Activity (Ci)
<b>High-Level Contaminated Systems:</b>			
LDS Letdown	1.26e+08	3.6e+09	2.08e+03
PAS Post Accident Sampling System			
PZR Pressurizer Relief			
RCS Reactor Coolant			
RHR Residual Heat Removal			
RSS Reactor Sampling			
SFP Spent Fuel Pool Cooling			
VCC Volume Control			
<b>Medium-Level Contaminated Systems:</b>			
BAS Boric Acid	1.25e+08	1.9e+06	1.08e+01
CWL Containment Water Level			
RCP RCP Seal Water			
RLC Radwaste Collection			
RMS Radiation Monitoring			
RWG Radwaste Gas			
RWL Radwaste Liquid			
CRS (Containment Spray) Recirculation			
SIS Safety Injection			
<b>Low-Level Contaminated Systems:</b>			
AFW Auxiliary Feedwater	3.18e+08	8.3e+03	1.21e-02
CCW Component Cooling			
CND Condensate			
SHA Sphere Hydrazine Addition			
CSS Condensate Sampling			
CVD Condensate Vents & Drains			
CVI Cryogenics			
CWS Circulating Water			
FES Flash Evaporator			
FPS Fire Protection			
FSS Feed Sampling			
FWH Feedwater Heaters			
FWS Feedwater			
MSS Main Steam			
MVS Miscellaneous Ventilation			
PSC Turbine Sample Cooling			
SDW Service Water			
SWC Salt Water Cooling			
TCW Turbine Cooling			

## Yankee Rowe

Yankee Rowe is a 167-MWe PWR with a startup date of August 19, 1960. It started commercial operation in July, 1961 and was shutdown in October, 1991 following 21 fuel cycles and 8,052 EFPD. In the 1993 decommissioning plan submitted to the NRC, systems with significant internal surface contamination were identified, as shown in Table A-10 (Yankee Atomic 1995).

Table A-10. Average Internal Contamination Levels of Reactor Systems at Yankee Rowe

System	Surface Contamination Level (dpm/100 cm <sup>2</sup> )
Main Coolant	7.1e+09
Spent Fuel Cooling	3.3e+08
Waste Disposal	1.2e+07
Primary Plant Vent & Drain	1.2e+07
Charging & Volume Control	1.2e+07
Shutdown Cooling	1.2e+07
Fuel Handling	1.7e+06
Letdown/Purification	1.4e+06
Primary Plant Sampling	1.4e+06
Safety Injection	1.4e+05
Safe Shutdown	1.4e+05
Vol. Control Heating & Cooling	1.2e+04
Vol. Control Vent. & Purge	1.2e+04
Post Accident H <sub>2</sub> Control	1.2e+04
Chemical Shutdown	1.1e+04

The data on facilities that have submitted decommissioning plans have limited applicability to a generic analysis because of: (1) their limited years of operation, (2) abnormal events and operating conditions that prompted premature shutdown and/or, (3) size and design of the facilities.

### A.3.2.3 Levels of Internal Surface Contamination Derived for Reference BWR

Internal surface contamination levels in BWR systems and piping reflect the radionuclide concentrations in the reactor coolant, steam and condensate. Summary estimates of activities in

corrosion films deposited on internal surfaces of equipment and piping are cited by Oak et al. (1980) for a Reference BWR.

The radionuclide composition of corrosion films is shown in Table A-11. About 86% of the estimated inventory at shutdown was due to two nuclides, Co-60 and Mn-54 (Co-60 constituted nearly half of the total inventory). It should be noted that internal surface deposited nuclides generally do not include large amounts of fission products. Although fission products do exist in the reactor coolant, they are generally soluble and remain in solution rather than plate out along with neutron-activated corrosion products. The buildup of coolant contaminants is controlled by the CVCS system, which continuously removes both insoluble (particulate) and soluble contaminants.

Table A-11. Activated Corrosion Products in the Reference BWR

Nuclide	Half-Life	Relative Activity at Various Times After Shutdown*			
		0	10 y	30 y	50 y
Cr-51	27.7 d	2.1e-02	—	—	—
Mn-54	312.1 d	3.9e-01	1.2e-04	—	—
Fe-59	44.5 d	2.5e-02	—	—	—
Co-58	70.88 d	9.3e-03	—	—	—
Co-60	5.271 y	4.7e-01	1.3e-01	9.1e-03	6.6e-04
Zn-65	244.26 d	6.1e-03	1.9e-07	—	—
Zr-95	64.02 d	4.0e-03	—	—	—
Nb-95	34.97 d	4.0e-03	—	—	—
Ru-103	39.27 d	2.3e-03	—	—	—
Ru-106	373.6 d	2.8e-03	3.2e-06	—	—
Cs-134	2.065 y	1.9e-02	—	—	—
Cs-137	30.07 y	3.4e-02	2.7e-02	1.7e-02	1.1e-02
Ce-141	32.5 d	3.0e-03	—	—	—
Ce-144	284.9 d	8.1e-03	1.1e-06	—	—
Total		1.0	1.5e-01	2.6e-02	1.1e-02

\* Activities of individual nuclides, normalized to the total activity at shutdown

The total radionuclide inventory has been estimated at 8,500 curies, with 6,300 curies associated with internal equipment surfaces and the remaining 2,200 curies associated with internal piping surfaces (see Table A-12).

Table A-12.  
Distribution of Activated Corrosion Products on Internal Surfaces of Reference BWR

Location	Surface Area ( m <sup>2</sup> )	Areal Activity Concentration (Ci/m <sup>2</sup> )	Total Surface Activity (Ci)
<b>Piping</b>	3.4e+04	6.5e-02	2.2e+03
<b>Equipment:</b>			
Reactor Building	8.6e+03	2.2e-01	1.9e+03
Turbine Building	2.0e+05	6.0e-03	1.2e+03
Radwaste & Control	1.4e+03	2.3e+00	3.2e+03
<b>Total</b>	2.4e+05	2.6e+00	8.5e+03

Source: Oak et al. 1980, vol. 1, Table 7.4-10

For the residual inventory of 6,300 curies on equipment, an estimated 30% was associated with equipment in the reactor building, about 19% was associated with the condenser and feed-water heaters located in the turbine building, and about 51% involved internal deposition on equipment in the radwaste and control building.

Of the 2,200 curies present in piping, approximately 56% were estimated to be associated with the reactor coolant piping and 44% with condensate piping. Presented below is a more thorough analysis of piping data.

### **Contaminated Piping**

Internal surface contamination levels of BWR piping can be most useful when grouped according to direct or indirect contact with reactor coolant, steam/air and condensate. Deposition levels for reactor coolant and condensate were based on empirical dose rate measurements that were correlated to contamination levels for a specific pipe size and schedule. A summary of measured dose rate data and derived deposition levels is shown in Table A-13.

Table A-14 provides a detailed accounting of radionuclide inventories derived for various size piping made of aluminum, carbon steel, and stainless steel in contact with reactor coolant, steam/air, or condensate.

Table A-13. Contact Dose Rate and Internal Surface Activity of BWR Piping

Medium in Pipes	Nominal O.D. (mm)	Wall Thickness (mm)	Contact Dose Rate (mR/hr)	Areal Activity Concentration (Ci/m <sup>2</sup> )
Reactor Coolant	610	59.5	700	1.1
Steam/Air	914	20.4	70	0.005
Condensate	610	26.0	50	0.05

### Contaminated Equipment

Contamination on internal surfaces of BWR equipment in contact with reactor coolant was estimated from measurements taken on the heat exchanger in the reactor coolant cleanup system. In general, equipment in contact with steam or condensate was assumed to reach the same levels as previously cited for BWR piping. Exceptions were the lower values assigned to steam surfaces for the turbine and feedwater heaters. Table A-15 provides estimates of contamination levels assigned to BWR equipment.

Table A-16 identifies the major system components and radionuclides inventories based on location and contact with reactor coolant, steam, condensate and radwaste.

#### A.3.2.4 Levels of Internal Surface Contamination for Reference PWR

Radioactive contamination levels associated with internal surfaces of piping and equipment for a Reference PWR have been estimated by Smith et al. (1978). At time of shutdown, the fractional contributions of various radionuclides deposited on internal surfaces of the primary loop of a PWR are shown in Table A-17.

Estimates of internal surface activity concentrations for major systems and components were based on models which correlated external dose rate measurements with internal contamination analyses, taking into account source geometry and shielding factors (see Table A-18). Empirical dose rate measurements showed that reactor vessel and steam generator internal surfaces in contact with primary coolant, on average, would yield contamination levels of about 0.23 Ci/m<sup>2</sup> at time of shutdown.

Table A-14. Estimates of Internal Contamination for Reference BWR Piping

Pipe Material/ Contact Medium	Outer Diameter (mm)																		Total		
	60			152			356			533			660			914					
	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)	L (m)	A (m <sup>2</sup> )	Act. (Ci)
Aluminum																					
Steam/Air	4,300	81	0.4	1,400	640	3.2	130	140	0.7	—	—	—	—	—	—	—	—	—	5,830	861	4
Condensate	—	—	—	14	6.7	0.3	—	—	—	—	—	—	—	—	—	—	—	—	14	7	0.3
Carbon Steel																					
Rx coolant	380	71	78	1,500	700	770	61	68	75	55	92	100	—	—	—	—	—	—	1,996	931	1,023
Steam/Air	1,200	220	1.1	1,800	880	4.4	5,600	6,300	32	1,200	2,000	10	950	200	9.8	440	1,300	6.3	11,190	10,900	64
Condensate	7,400	1,400	7.0	8,300	3,900	200	5,100	5,700	280	2,800	4,600	230	370	770	38	210	610	31	24,180	16,980	786
Stainless Steel																					
Rx coolant	8	1.5	1.6	34	16	18	61	68	75	55	92	100	—	—	—	—	—	—	158	178	195
Steam/Air	280	53	0.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	280	53	0
Condensate	7,000	1,300	66	1,600	780	39	220	240	12	—	—	—	—	—	—	—	—	—	8,820	2,320	117
<b>Total</b>	<b>20,568</b>	<b>3,127</b>	<b>154</b>	<b>14,648</b>	<b>6,923</b>	<b>1,035</b>	<b>11,172</b>	<b>12,516</b>	<b>475</b>	<b>4,110</b>	<b>6,784</b>	<b>440</b>	<b>1,320</b>	<b>970</b>	<b>48</b>	<b>650</b>	<b>1,910</b>	<b>37</b>	<b>52,468</b>	<b>32,229</b>	<b>2,189</b>

Note: Average contamination level = 68 mCi/m<sup>2</sup> (1.5 x 10<sup>9</sup> dpm/100 cm<sup>2</sup>)

Table A-15. Summary of Contamination Levels in BWR Equipment

Equipment Category	Areal Activity Concentration (Ci/m <sup>2</sup> )
<b>Reactor Coolant Equipment</b>	3.6e-01
<b>Steam Equipment</b>	5.0e-03
Turbine	5.0e-04
<b>Condensate Equipment</b>	5.0e-02
Main Condenser	5.0e-03
Feedwater Heaters	5.0e-03
<b>Concentrated Waste Tanks/Equipment</b>	5.0e+00

The total surface activity on the reactor vessel and its internal components, which have a total surface area of 570 m<sup>2</sup>, was estimated to be about 130 Ci. The surface activity on the four steam generators, which have a total mass of 1,251 t and a combined surface area of about 19,000 m<sup>2</sup>, was estimated to be approximately 4,400 Ci, which represents 90% of the total deposited activity. The areal concentration of activated corrosion products in the 89-metric ton pressurizer was assumed to be about 0.04 Ci/m<sup>2</sup>. Since the internal surface area is about 87 m<sup>2</sup>, the total deposited activity was estimated to be about 4 Ci.

Table A-16. Estimated Internal Surface Activities in BWR Systems

Building/System	Total Internal Area (m <sup>2</sup> )	Areal Activity Concentration (Ci/m <sup>2</sup> )	Total Activity (Ci)
<b>Reactor Building</b>			
Fuel Pool Heat Exchangers	8.0e+02	5.0e-02	4.0e+01
Skimmer Surge Tanks	1.0e+02	5.0e-02	5.0e+01
Fuel Pool, Rx Wall, Dryer & Sep. Pool	1.4e+03	5.0e-02	7.0e+01
RBCC Water Heat Exchangers	1.8e+03	5.0e-02	9.0e+01
RMCU Regenerative Heat Exchangers	2.5e+02	3.6e-01	9.0e+01
RWCU Nonregenerative Heat Exchangers	1.7e+02	3.6e-01	6.0e+01
RHR Heat Exchangers	1.5e+03	3.6e-01	5.4e+02
Reactor Vessel	2.6e+03	3.6e-01	9.4e+02
Total	8.6e+03		1.9e+03

Table A-16 (continued)

Building/System	Total Internal Area (m <sup>2</sup> )	Areal Activity Concentration (Ci/m <sup>2</sup> )	Total Activity (Ci)
<b>Turbine Generator Building</b>			
Main Condenser	7.9e+04	5.0e-03	3.9e+02
Steam Jet Air Ejector Condenser	1.6e+03	5.0e-02	8.0e+01
Gland Seal Steam Condenser	3.5e+02	5.0e-02	1.7e+01
Condensate Storage Tanks	1.6e+03	5.0e-02	8.0e+01
Low-Pressure Feedwater Heaters	7.5e+04	5.0e-03	3.7e+02
Evaporator Drain Tanks	1.0e+01	5.0e-02	5.0e-01
Reheater Drain Tanks	8.4e+02	5.0e-02	4.2e+01
Moisture Separator Drain Tank	3.0e+01	5.0e-03	1.5e-01
Main Turbine	2.6e+03	5.0e-04	1.3e+00
Steam Evaporator	2.0e+03	5.0e-03	1.0e+01
Turbine Bypass Valve Assembly	1.5e+01	5.0e-03	7.5e-01
Moisture Separator Reheaters	1.8e+04	5.0e-03	9.0e+01
Seal Water Liquid Tank	1.2e+01	5.0e-02	6.0e-01
Pumped Drain Tank	2.7e+01	5.0e-02	1.4e+00
High-Pressure Feedwater Heaters	1.7e+04	5.0e-03	8.5e+01
Total	2.0e+05		1.2e+03
<b>Radwaste and Control Building</b>			
Condensate Phase Separator Tanks	1.8e+02	5.0e+00	9.0e+02
Condensate Backwash Receiver Tank	8.5e+01	5.0e+00	4.2e+02
Waste Collector Tank	1.0e+02	5.0e-02	5.0e+00
Waste Surge Tank	1.9e+02	5.0e+00	9.5e+02
Waste Sample Tanks	1.6e+02	5.0e-02	8.0e+00
Floor Drain Collector Tank	1.1e+02	5.0e-02	5.5e+00
Waste Sludge Phase Separator Tank	6.1e+01	5.0e+00	3.0e+02
Floor Drain Sample Tank	7.8e+01	5.0e-02	3.9e+00
Chemical Waste Tanks	1.5e+02	5.0e-02	7.5e+00
Distillate Tanks	1.5e+02	5.0e-02	7.5e+00
Detergent Drain Tank	3.2e+01	5.0e-02	1.6e+01
Decontamination Solution Conc. Waste Tk.	2.3e+01	5.0e+00	1.2e+02
Spent Resin Tank	1.3e+01	5.0e+00	6.5e+01
Cleanup Phase Separator Tanks	6.8e+01	5.0e+00	3.4e+02
Decontamination Solution Concentrator	1.9e+01	5.0e+00	9.5e+01
Total	1.4e+03		3.2e+03

Source: Oak et al. 1980, vol. 2, Table E.2-7

RCS piping includes those sections of piping interconnecting the reactor vessel, steam generators, reactor coolant pumps and various other components, as shown in Figure A-3. RCS

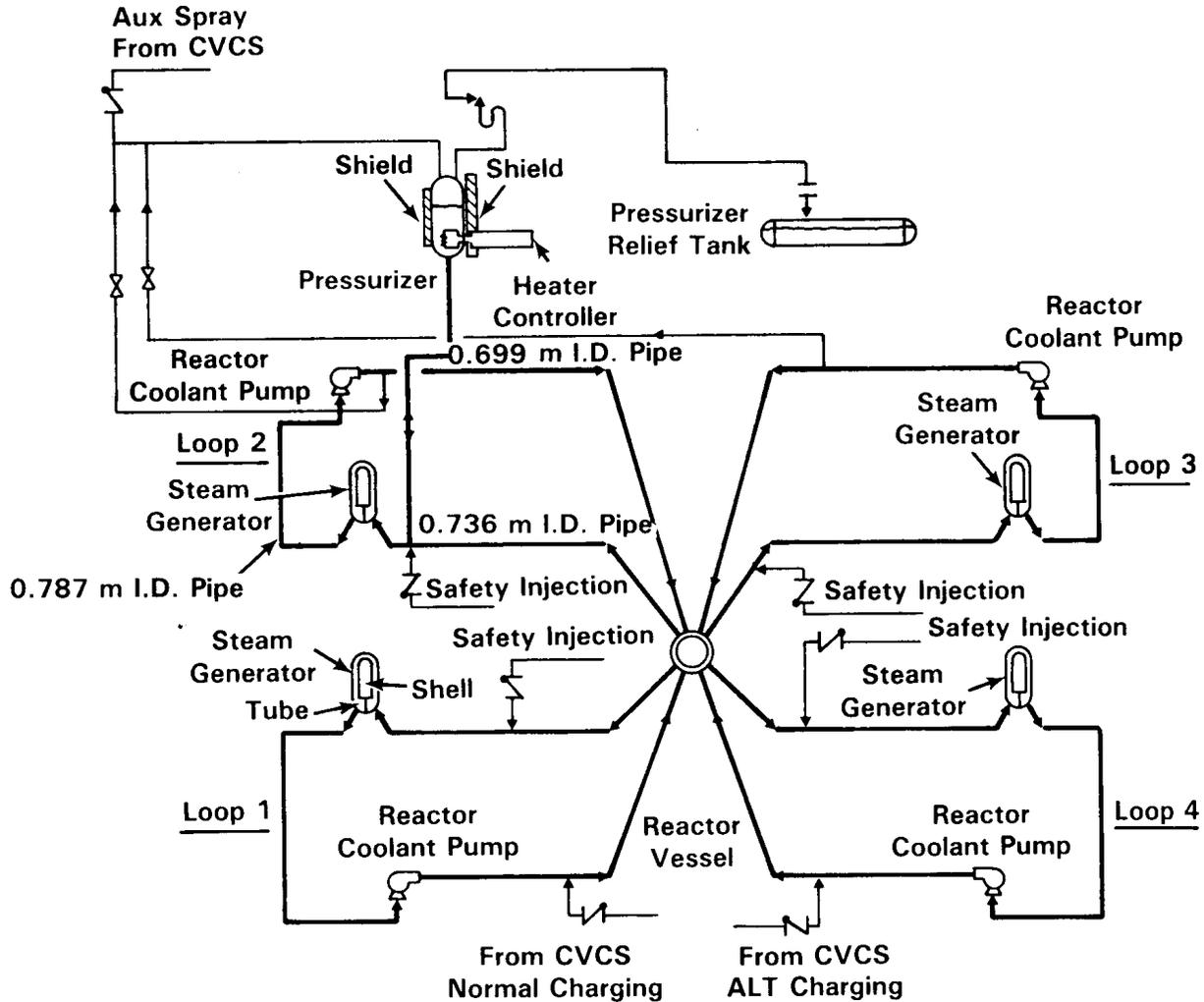


Figure A-3. Reactor Coolant System in a Four-Loop PWR (Abel et al. 1996)

pipng primarily involves large diameter, thick-walled pipes. The inside diameter typically ranges from 699 mm to 787 mm, with a corresponding wall thickness of between 59 and 66 mm. From dose rate measurements—about 600 mR/hr—the internal surface activity concentration on RCS piping was estimated at 0.86 Ci/m<sup>2</sup>. The total activity on the RCS piping, which has an internal surface area of about 190 m<sup>2</sup> and a mass of 100 t, is estimated to be 160 Ci.

The average activity concentration on the inner surfaces of non-RCS or auxiliary system piping is estimated to be about 0.06 Ci/m<sup>2</sup>, based on external dose rate measurements. This value, together with the pipe specifications listed in Table A-19, yields a total surface activity of about 71 Ci on the inner surfaces of all non-RCS PWR piping.

Table A-17. Internal Surface Contamination in the Reference PWR Primary System

Radionuclide	Half-Life	Areal Activity Concentration ( $\mu\text{Ci}/\text{m}^2$ )	Relative Activity at Various Times After Shutdown*			
			0	10 y	30 y	50 y
Cr-51	27.7 d	5.30e+03	2.40e-02	—	—	—
Mn-54	312.1 d	8.00e+03	3.60e-02	1.1e-05	—	—
Fe-59	2.73 y	1.80e+03	8.20e-03	—	—	—
Co-58	70.88 d	1.00e+05	4.60e-01	—	—	—
Co-60	5.271 y	7.10e+04	3.20e-01	8.6e-02	6.2e-03	4.5e-04
Zr-95	64.02 d	8.80e+03	5.60e-02	—	—	—
Nb-95	34.97 d	1.20e+04	5.60e-02	—	—	—
Ru-103	39.27 d	5.90e+03	2.60e-02	—	—	—
Cs-137	30.07 y	2.60e+02	1.20e-03	9.5e-04	6.0e-04	3.8e-04
Ce-141	32.5 d	1.50e+04	6.60e-02	—	—	—
Total		2.30e+05	1.0	8.7e-02	6.8e-03	8.3e-04

Source: Smith et al. 1978, vol. 1

\* Activities of individual nuclides, normalized to the total activity at shutdown

Table A-18. Activated Corrosion Products on the Interiors of PWR Systems

Systems	Surface Area ( $\text{m}^2$ )	Areal Activity Concentration ( $\text{Ci}/\text{m}^2$ )	Total Activity (Ci)
Reactor Vessel and Internals	5.7e+02	0.23	130 <sup>a</sup>
Steam Generators	1.9e+04	0.23	4,400
Pressurizer	8.7e+01	0.05	4
Piping (Except RCS)	1.1e+03	0.05	60
RCS Piping	1.9e+02	0.84	160
Total	2.1e+04		4,800

Source: Smith et al. 1978, vol. 2, Table C.4-5

<sup>a</sup> Excluding volumetrically distributed activation products

### A.3.3 Contamination of External Surfaces of Equipment and Structural Components

External surfaces of system components as well as floors, walls and structural components become contaminated over the operating lifetime of a nuclear power plant from leaks or spills of radioactive materials originating from the reactor coolant. While most liquid contamination

remains localized in the vicinity of the leak or spill, some contamination may experience limited transfer through physical contact. More widespread contamination of external surfaces occurs when contaminants become airborne and passively settle out. Airborne contaminants are also the principal source of contamination of ducts, fans, filters and other equipment that are part of the heating and ventilation and air conditioning systems (HVAC).

Table A-19. Non-RCS Contaminated PWR Piping

Nominal Pipe Size (in.)	Schedule	I.D. (in.)	Length (m)	Mass (kg)	Inside Area (m <sup>2</sup> )	Total Activity (Ci)
½	80	0.546	120	198	5.2	0.3
	160	0.464	120	238	4.4	0.3
¾	40	0.824	240	205	15.8	0.9
	80	0.742	360	400	21.3	1.3
	160	0.612	570	1,675	27.8	1.7
1	40	1.049	60	152	5.0	0.3
	80	0.957	180	590	13.7	0.8
	160	0.815	420	1,800	27.3	1.6
1½	40	1.610	120	493	15.4	0.9
	80	1.500	330	1,811	39.5	2.4
	160	1.338	540	3,967	57.7	3.5
2	40	2.067	300	1,655	49.5	3.0
	80	1.939	480	3,642	74.3	4.5
	160	1.687	1,050	11,850	141.3	8.5
3	160	2.624	140	2,985	29.3	1.8
4	160	3.438	180	6,128	49.4	3.0
6	160	5.187	300	20,972	124.2	7.5
8	160	6.813	140	15,924	76.1	4.6
10	140	8.500	365	29,750	247.6	14.9
12	140	10.126	90	18,370	72.7	4.4
14	140	11.188	100	25,475	89.3	5.4
Total			6,205	148,280	1186.9	71.2

Radionuclides typically found in the primary coolant and their relative abundance in a PWR and BWR are given in Table A-20 and Table A-21, respectively.

Table A-20. Radionuclides in Primary Coolant in the Reference PWR

Radionuclide	Half-Life	Relative Activity at Various Times After Shutdown*			
		0	10 y	30 y	50 y
Cr-51	27.7 d	6.9e-04	—	—	—
Mn-54	312.1 d	1.4e-03	4.2e-07	—	—
Fe-55	2.73 y	2.2e-02	1.7e-03	1.1e-05	6.7e-08
Fe-59	44.5 d	8.7e-04	—	—	—
Co-58	70.88 d	7.5e-03	—	—	—
Co-60	5.271 y	7.5e-02	2.0e-02	1.5e-03	1.0e-04
Sr-89	50.52 d	1.2e-03	—	—	—
Sr-90+D	28.78 y	6.9e-04	5.4e-04	3.4e-04	2.1e-04
Zr-95	64.02 d	2.5e-04	—	—	—
Nb-95	34.97 d	2.5e-04	—	—	—
Te-129m	33.6 d	3.1e-04	—	—	—
I-131	8.04 d	1.4e-02	—	—	—
Cs-134	2.065 y	1.2e-01	4.2e-03	5.1e-06	6.2e-09
Cs-136	13.16 d	1.1e-03	—	—	—
Cs-137	30.07 y	7.5e-01	6.0e-01	3.8e-01	2.4e-01
Total		1.0	0.62	0.38	0.24

Source: Smith et al. 1978, vol. 1

\* Activities of individual nuclides, normalized to the total activity at shutdown

The amount of external surface contamination following 40 years of operation is likely to vary significantly among nuclear power plants and is influenced by fuel integrity, primary coolant chemistry, operational factors and reactor performance. A key operational factor is the effort expended to clean up spills and to decontaminate accessible areas on an ongoing basis.

Although all nuclear utilities conduct routine radiological surveys that assess fixed and removable surface contamination, only limited data have been published in the open literature from which average contamination estimates can be derived. In this section, estimates of external surface contamination are provided that reflect (1) modeled data, (2) data published in the open literature and (3) data from individual utilities that have submitted a decommissioning plan.

Table A-21. Radionuclide Concentrations in Reactor Coolant of Reference BWR

Radionuclide	Half-Life (days)	Specific Activity ( $\mu\text{Ci/g}$ )	Relative Activity at Various Times After Shutdown*			
			0	10 y	30 y	50 y
P-32	14.28 d	2e-04	1.1e-03	—	—	—
Cr-51	27.7 d	5e-03	5.3e-02	—	—	—
Mn-54	312.1 d	6e-05	7.2e-04	2.2e-07	—	—
Fe-55	2.73 y	1e-03	3.7e-01	2.9e-02	1.8e-04	1.1e-06
Fe-59	44.5 d	3e-05	5.3e-04	—	—	—
Co-58	70.88 d	2e-04	5.6e-03	—	—	—
Co-60	5.271 y	4e-04	2.9e-01	7.8e-02	5.6e-03	4.0e-04
Ni-63	100.1 y	1e-06	3.4e-03	3.2e-03	2.8e-03	2.4e-03
Zn-65	244.26 d	2e-04	1.8e-02	5.7e-07	—	—
Sr-89	50.52 d	1e-04	2.0e-03	—	—	—
Sr-90 +D	28.78 y	6e-06	1.5e-02	1.2e-02	7.3e-03	4.5e-03
Y-91	58.5 d	4e-05	8.1e-04	—	—	—
Zr-95	64.02 d	7e-06	1.6e-04	—	—	—
Ru-103	39.27 d	2e-05	2.9e-04	—	—	—
Ru-106	373.6 d	3e-06	3.9e-04	—	—	—
Ag-110m	249.8 d	1e-06	8.8e-06	3.5e-10	—	—
Te-129m	33.6 d	4e-05	4.9e-04	—	—	—
I-131	8.04 d	5e-03	1.5e-02	—	—	—
Cs-134	2.065 y	3e-05	8.8e-03	3.1e-04	3.7e-07	4.5e-10
Cs-136	13.16 d	2e-05	1.0e-04	—	—	—
Cs-137	30.07 y	7e-05	1.8e-01	1.4e-01	9.0e-02	5.7e-02
Ba-140 +D	12.75 d	4e-04	2.0e-03	—	—	—
Ce-141	32.5 d	3e-05	3.4e-04	—	—	—
Ce-144	284.9 d	3e-06	2.9e-04	4.0e-08	—	—
Pr-143	13.57 d	4e-05	2.0e-04	—	—	—
Nd-147	10.98 d	3e-06	1.2e-05	—	—	—
Total		1.3e-02		2.7e-01	1.1e-01	6.4e-02

\* Activities of individual nuclides, normalized to the total activity at shutdown

### A.3.3.1 Data for Reference Facilities

Oak et al. (1980) have modeled the surface contamination on structures of the Reference BWR. The model was based on an assumed release rate of one liter of primary coolant per day for 40 years. Levels of deposited contaminants on external surfaces were correlated to ambient dose rates by means of the computer code ISOSHL and divided into two discrete categories. The first category is low-level contamination, defined by dose rates of 10 mR/hr in air at 1 meter from the surface. The second category was defined as higher contamination with dose rates of 100 mR/hr in air at 1 meter from the surface. Based on the radionuclide composition of Reference BWR coolant, these two contamination levels were estimated to correspond to areal activity concentrations of  $2.5 \times 10^{-3}$  Ci/m<sup>2</sup> and  $2.5 \times 10^{-2}$  Ci/m<sup>2</sup>, respectively.

Table A-22 summarizes the distribution of external surface contaminants at shutdown. The total deposited activity on structural surfaces in the Reference BWR was estimated to be 114 curies.

Table A-22. Surface Contamination Levels for Reference BWR at Shutdown

Building	Surface Area (m <sup>2</sup> )	Deposited Activity (Ci)	Surface Contamination Level at Shutdown (dpm/100 cm <sup>2</sup> )
<b>Reactor Building</b>	<b>5145</b>	<b>74</b>	<b>3.19e+08</b>
Contamination Level 1 <sup>a</sup>	2403	5.7	5.27e+07
Contamination Level 2 <sup>b</sup>	2742	68.3	5.53e+08
<b>Turbine Generator Bldg.</b>	<b>1817</b>	<b>4.4</b>	<b>5.38e+07</b>
Contamination Level 1 <sup>a</sup>	1767	3.2	4.02e+07
Contamination Level 2 <sup>b</sup>	50	1.2	5.33e+08
<b>Radwaste &amp; Control Bldg.</b>	<b>1953</b>	<b>35.8</b>	<b>4.07e+08</b>
Contamination Level 1 <sup>a</sup>	579	1.4	5.37e+07
Contamination Level 2 <sup>b</sup>	1374	34.4	5.56e+08
<b>Total</b>	<b>8915</b>	<b>114.2</b>	<b>2.84e+08</b>

Source: Oak et al. 1980, vol. 2, Table E.2-10

<sup>a</sup> Contamination Level 1 corresponds to  $2.5 \times 10^{-3}$  Ci/m<sup>2</sup>.

<sup>b</sup> Contamination Level 2 corresponds to  $2.5 \times 10^{-2}$  Ci/m<sup>2</sup>.

Table A-23 provides a more detailed breakdown of contamination levels by identifying major equipment/systems that are located within each of the aforementioned facility buildings.

Table A-23. Estimated External Structural Contamination in the Reference BWR

Building/Associated Equipment/System/Structure	Contaminated Area (m <sup>2</sup> )	Contamination Level	Deposited Activity (Ci)
<b>Reactor Building</b>			
Containment Atmosphere Control	1.6e+01	1	4.0e-02
Condensate (Nuclear Steam)	3.3e+01	1	8.2e-02
Control Rod Drive	1.8e+02	1	4.5e-01
Equipment Drain (Radioactive)	1.8e+01	2	4.5e-01
Floor Drain (Radioactive)	7.4e+01	2	1.8e+00
Fuel Pool Cooling & Cleanup	1.2e+03	1	3.0e+00
Fuel Pool Cooling & Cleanup	2.8e+02	2	7.0e+00
High-Pressure Core Spray	1.1e+02	1	2.7e-01
Low-Pressure Core Spray	1.4e+01	1	3.5e-02
Main Steam	3.0e+02	1	7.5e-01
Miscellaneous Wastes (Radioactive)	8.3e+01	1	2.1e-01
Reactor Building Closed Cooling	1.2e+01	1	3.0e-02
Reactor Core Isolation Cooling	1.5e+01	1	3.8e-02
Reactor Water Cleanup	1.5e+02	1	3.8e-01
Reactor Water Cleanup	1.7e+02	2	4.2e+00
Residual Heat Removal	1.7e+02	1	4.2e-01
Standby Gas Treatment	4.0e+01	1	1.0e-01
Traversing Incore Probe	8.0e+01	1	2.0e-01
Primary Containment	2.2e+03	2	5.5e+01
<b>Total</b>			<b>7.4e+01</b>
<b>Turbine Generator Building</b>			
Air Removal	3.9e+01	1	9.7e-02
Condensate (Nuclear Steam)	6.6e+02	1	1.6e-01
Condenser Off Gas Treatment	1.8e+02	1	4.5e-01
Equipment Drain (Radioactive)	2.5e+01	2	6.2e-01
Floor Drain (Radioactive)	2.5e+01	2	6.2e-01
Heater Drain	9.1e+01	1	2.3e-01
Main Steam	1.7e+02	1	4.2e-01
Miscellaneous Drain & Vent	1.9e+01	1	4.7e-02
Reactor Feedwater	6.9e+02	1	1.7e+00
Miscellaneous Wastes (Radioactive)	9.0e+00	1	2.2e-02
<b>Total</b>			<b>4.4e+00</b>

Table A-23 (continued)

Building/Associated Equipment/System/Structure	Contaminated Area (m <sup>2</sup> )	Contamination Level	Deposited Activity (Ci)
<b>Radwaste and Control Building</b>			
Condensate Filter Demineralizer	3.6e+02	2	9.0e+00
Condenser Off Gas Treatment	3.2e+02	1	8.0e-01
Equipment Drain (Radioactive)	4.3e+01	1	1.1e-01
Equipment Drain (Radioactive)	1.8e+02	2	4.5e+00
Floor Drain (Radioactive)	1.2e+01	1	3.0e-02
Floor Drain (Radioactive)	1.9e+02	2	4.8e+00
Floor Pool Cooling & Cleanup	5.4e+01	2	1.4e+00
Miscellaneous Wastes (Radioactive)	2.4e+01	1	6.0e-02
Miscellaneous Wastes (Radioactive)	1.9e+02	2	4.8e+00
Process Waste (Radioactive)	1.8e+02	1	4.5e-01
Process Waste (Radioactive)	2.7e+02	2	6.7e+00
Reactor Water Cleanup	1.3e+02	2	3.2e+00
<b>Total</b>			<b>3.6e+01</b>

Source: Oak et al. 1980

Note: Estimated total deposited radioactivity on contaminated external surfaces =  $1.14 \times 10^2$  Ci

### Model Estimates Versus Empirical Data

External surface contamination corresponding to Level 1 ( $2.5 \times 10^{-3}$  Ci/m<sup>2</sup> or  $5.2 \times 10^7$  dpm/100 cm<sup>2</sup>) and Level 2 ( $2.5 \times 10^{-2}$  Ci/m<sup>2</sup> or  $5.5 \times 10^8$  dpm/100 cm<sup>2</sup>) is not uncommon and has been observed in most reactor facilities. Table A-24 presents study data that focused on the most highly contaminated surfaces at six nuclear power plants (Abel et al. 1986). Contamination levels corresponding to modeled values (i.e., Level 1 and Level 2), however, were restricted to small areas that had experienced spills, leaks, or intense maintenance, such as the reactor sump area, RCS coolant pumps and radwaste system components. The study data also showed that when surfaces were coated with sealant or epoxy paint, nearly all contamination resided on or within the surficial coating and was readily removable.

In summary, the modeled external surface contamination levels cited by Oak et al. (1980) for the Reference BWR appear excessive in terms of their projected surface areas and total plant inventory. The primary model parameter regarding the release of one liter of primary coolant per day that is allowed to buildup over a forty-year period of plant operation is not only without

technical basis but ignores the ongoing decontamination efforts that exist at all nuclear facilities. For these reasons, the modeled data cited by Oak et al. (1980) are not considered suitable for characterizing the contaminated material inventories of BWR power plants.

Table A-24. External Surface Activity Concentrations at Six Nuclear Generating Stations

Radionuclide	Areal Activity Concentration		
	Range (pCi/cm <sup>2</sup> )	Average (dpm/100 cm <sup>2</sup> )	N*
Co-60	590 - 460,000	2.4e+07	5
Ni-59	30 - 2,400	1.9e+05	3
Ni-63	3,100 - 6,400	1.0e+06	2
Sr-90	1.6 - 480	3.7e+04	4
Tc-99	0.27 - 2.4	3.5e+02	3
Cs-137	550 - 2.0 E6	8.1e+07	6
Eu-152	9 - 3,100	2.2e+05	3
Eu-154	90 - 1,500	1.5e+05	3
Eu-155	10 - 500	1.3e+04	2
Pu-238	0.025 - 48	3.1e+03	4
Pu-239, 240	0.089 - 21	1.7e+03	4
Am-241	0.10 - 30	1.9e+03	4
Cm-244	0.013 - 0.026	3.5e+00	3

\*Number of reactor units included in calculation

### A.3.3.2 Surface Contamination Levels Reported by Facilities Preparing for Decommissioning

#### **PWR**

By coincidence (as was previously noted), the Trojan Nuclear Plant (TNP), which was used as the Reference PWR facility by Smith et al. (1978), has been permanently shutdown and has submitted a decommissioning plan. External surface contamination inventories at this facility are summarized in TNP's decommissioning plan and have been reproduced in Table A-25. Estimates were based on historical survey data and recent structural surveys performed in support of the radiological site characterization required by the decommissioning plan.

Combined radionuclide inventories in the containment building, auxiliary building, fuel building and the main steam support structure are estimated to be 30 mCi. Note that this value is about

three orders of magnitude lower than the estimate for the Reference BWR modeled by Oak et al. (1980), presented in Table A-23.

Table A-25. Radionuclide Inventories on External Surfaces at Trojan Nuclear Plant

Structure	Total Activity (mCi)
Containment Building	24
Auxiliary Building	2
Fuel Building	1
Main Steam Support Structure	1
Turbine Building	2
Total	30

More detailed data relating to contamination of external surfaces at TNP were recently cited in a draft report issued by the NRC (1994). The survey data primarily measured removable floor contamination levels obtained by smears. However, such measurements may reasonably be assumed to also represent metal surfaces of reactor systems and structural components.

A summary of removable external surface contamination levels at TNP are given in Table A-26.

Table A-26. Contamination of Floor Surfaces at Trojan Nuclear Plant Prior to Decommissioning

Building	Total Area (m <sup>2</sup> )	Contaminated		Removable Surface Contamination (dpm/100 cm <sup>2</sup> )
		Fraction (%)	Area (m <sup>2</sup> )	
Containment	1,900	100	1,900	1,100 - 55,000
Auxiliary (6 levels)	4,000	1 - 5	40 - 200	< 1,100 - 7,900
Fuel Building (5 levels)	5,000	1 - 5	50 - 250	< 1,100 - 5,000
Turbine Building	5,700*	<< 1	~ 0	< 1,000
Control Building	700*	<< 1	~ 0	< 1,000

Source: NRC 1994

\* per level

The auxiliary and fuel buildings also exhibited some areas of floor contamination, but not to the extent of that observed in the reactor containment building. Based on survey reports, about 1% to 5% of the floor area (representing about 40 m<sup>2</sup> to 200 m<sup>2</sup>) in the auxiliary building has radioactive contamination levels in the range of 1,100 to 7,900 dpm/100 cm<sup>2</sup>. The fuel handling

building also has a small area of contaminated floor, ranging from 50 m<sup>2</sup> to 250 m<sup>2</sup>, with contamination levels ranging of about 1,100 to 5,000 dpm per 100 cm<sup>2</sup>.

Other buildings, including the turbine building and the control building, did not have measurable, removable contamination on any surfaces.

It is important to note, however, that the quantitative estimates in Table A-26 reflect contamination that is removable (i.e., by wiping a 100 cm<sup>2</sup> area with a dry filter paper). Reasonable estimates of total surficial contamination levels (i.e., fixed and removable) may be obtained by multiplying values in Column 5 of Table A-26 by a factor whose value may range from 5 to 10.

## **BWR**

Values similar to those reported in the TNP's decommissioning plan have also been reported in the decommissioning plan submitted for Humboldt Bay Unit 3 (Pacific Gas and Electric 1994). Excerpts of survey measurements (as they appear in the decommissioning plan) are shown in Tables A-27 and A-28. Horizontal surfaces (i.e., floors) exhibited contamination levels that, on average, were about one order of magnitude higher than vertical surfaces (i.e., walls) with values ranging from below detection limits up to several million dpm per 100 cm<sup>2</sup> for certain floor areas (e.g., under the reactor vessel). When relatively small areas of high contamination are excluded, average external surface contamination was generally between 5,000 and 100,000 dpm/100 cm<sup>2</sup>.

From the above-cited data, it is concluded that, within the common variability of contamination levels in nuclear plants, the survey data reported in decommissioning plans for the Trojan and Humboldt Bay facilities provide a reasonable basis for estimating surface contamination levels at other PWR and BWR power plants, respectively.

## **A.4 BASELINE METAL INVENTORIES**

### **A.4.1 Reference PWR**

The total amounts of metals contained in significant quantities in a typical 1,000 MWe PWR power plant have been quantified in a 1974 study of material resource use and recovery in nuclear power plants (Bryan and Dudley 1974). Material estimates were made using various methods that included: (1) amounts of raw materials purchased for construction (e.g., reinforcing steel and structural steel required for construction), (2) weights of materials contained in

equipment and machinery based on manufacturers' specifications and technical journals (e.g., determination of carbon steel, stainless steel, copper and other metals in electric motors); and (3) the U.S. Atomic Energy Commission facility accounting system, which identified individual items.

Summary estimates of composite materials used to construct a 1971-vintage 1,000 MWe PWR power plant are given in Table A-29.

Carbon steel is the predominant metal used in the construction of a nuclear power plant. It is used in piping and system components when the need for corrosion resistant stainless steel is not of significant importance. A large percentage is also used in structural components that include rebar, I-beams, plates, grates and staircases. A breakdown of material quantities used in reactor plant structures and plant systems is provided in Table A-30. Structural components comprise 16,519 t out of a total of 32,731 t of carbon steel, with the remainder used in plant equipment. Of the more than 16,000 t of carbon steel employed in plant equipment/systems, 10,958 t are contained in turbine plant equipment. Barring significant leakage in steam generators, equipment in this grouping as well as electric plant equipment, equipment identified as "miscellaneous," and "structures" are not likely to be exposed to radioactive contamination and are therefore not likely to contribute significant quantities of residually contaminated scrap metal.

The primary sources of contaminated scrap metal in a PWR are underlined in Table A-30 and involve all items associated with reactor plant equipment with additional quantities contributed by "Fuel Storage," certain structural components, HVAC systems and other items that are identified in detail in Section A.5.

Table A-30 also shows that the use of corrosion resistant stainless steel is almost totally confined to reactor plant and turbine plant systems. Of the total 2,080 t of stainless steel, essentially all of the 1,154.6 t associated with reactor plant systems and the 21.1 t that line the fuel pool can be assumed to be contaminated.

#### A.4.2 Reference BWR

Inventories for a 1,000-MWe BWR reference plant have been estimated by adjusting Bryan and Dudley's 1974 Reference PWR plant data taking into account the characteristics of a BWR (Oak et al. 1980).

Table A-27. Radiation Survey Data for Humboldt Bay Refueling Building<sup>a</sup>

Location		Dose Rate <sup>b</sup> (mR/h)		Contamination Levels ( $\mu\text{Ci}/100\text{cm}^2$ )			
				Contact <sup>c</sup>		Smearable	
		Gamma	Beta	Alpha	Beta-Gamma	Alpha	Beta-Gamma
+12 ft elevation	floor	10	<1	f	3.6e-02	3.9e-06	1.1e-03
	wall			f	9.8e-03	2.2e-06	3.3e-04
Access Shaft -2 ft elevation	floor	7 <sup>g</sup>	h	f	1.6e-02	7.1e-06	1.5e-03
	wall			f	2.1e-03	f	2.7e-05
-14 ft elevation	floor	2 <sup>g</sup>	0	f	4.2e-03	4.7e-06	2.3e-03
	wall			f	2.4e-03	2.3e-06	7.6e-04
-24 ft elevation	floor	1 <sup>g</sup>	h	f	3.1e-03	1.4e-05	2.4e-03
	wall			f	1.0e-03	f	f
-34 ft elevation	floor	1 <sup>g</sup>	h	f	2.1e-03	1.2e-05	3.0e-03
	wall			f	f	f	f
-44 ft elevation	floor	7 <sup>g</sup>	1.5	f	8.3e-02	4.5e-06	1.3e-03
	wall			f	1.0e-02	f	2.7e-05
-54 ft elevation	floor	18	1.1	f	1.2e-01	4.5e-06	1.2e-03
	wall			f	2.1e-02	f	f
-66 ft elevation	floor	12	0	f	1.4e-01	2.3e-06	6.1e-04
	wall			f	6.4e-02	f	f
Cleanup: HX Room -2 ft elevation	floor	65	0	f	1.0e-01	2.1e-05	9.4e-03
	wall			f	4.2e-02	f	1.9e-05
Cleanup: Demin Room -2 ft elevation	floor	6	1.5	f	2.1e-01	1.0e-04	4.2e-02
	wall			f	2.1e-03	2.0e-06	3.5e-04
Shutdown: HX Room -14 ft elevation	floor	55	1.1	f	f	3.7e-06	2.8e-03
	wall			f	2.1e-02	2.8e-07	2.0e-05
West Wing -66 ft elevation	floor	110	7.5	f	f	1.2e-05	2.7e-03
	wall			f	9.6e-02	5.6e-07	f
Under Reactor -66 ft elevation	floor	23	21	1.7e-03	2.0e+00	9.0e-04	3.3e-01
	wall			f	3.2e-02	6.5e-05	4.4e-03
New Fuel Vault +0 ft elevation	floor	5	47	3.4e-04	2.3e+00	1.9e-05	5.4e-03
	wall			f	f	1.1e-06	6.3e-04
TBDT Area -14 ft elevation	floor	23	35	f	1.6e-01	4.2e-06	9.6e-04
	wall			f	3.4e+00	1.1e-06	9.1e-03

<sup>a</sup> Average values of PG&E survey conducted May 1984 unless otherwise specified.

<sup>b</sup> Ion chamber

<sup>c</sup> Minimum sensitivity: alpha:  $1 \times 10^{-4} \mu\text{Ci}/100\text{cm}^2$   
 beta: Cutie Pie  $5 \times 10^{-3} \mu\text{Ci}/100\text{cm}^2$   
 HP-210  $2 \times 10^{-6} \mu\text{Ci}/100\text{cm}^2$

<sup>d</sup> Based on Cs-137

<sup>e</sup> Based on Sr-90 (10%), Co-60 (45%) and Cs-137 (45%)

<sup>f</sup> Not detected

<sup>g</sup> Previous survey

<sup>h</sup> Data not recorded

Table A-28. Radiation Survey Data for Humboldt Bay Power Building<sup>a</sup>

Location		Dose Rate <sup>b</sup> (mR/h)		Contamination Levels ( $\mu\text{Ci}/100\text{cm}^2$ )			
				Contact <sup>c</sup>		Smearable	
		Gamma	Beta	Alpha	Beta-Gamma	Alpha	Beta-Gamma
Condensor/ Demineralizer Cubicle	floor	11	0	f	3.2e-02	8.5e-06	1.4e-03
	wall			f	3.2e-02	f	9.7e-05
Condensor/ Demineralizer Regeneration Room	floor	14	1.5	2.6e-04	3.5e-02	1.1e-05	2.7e-03
	wall			1.0e-03	7.1e-02	1.1e-05	1.5e-03
Condensor/ Demineralizer Operations Area	floor	14 <sup>g</sup>	h	f	3.5e-03	1.4e-06	1.5e-04
	wall			f	8.8e-03	f	6.1e-05
Condensor Pump Room	floor	13 <sup>g</sup>	h	f	f	2.0e-06	5.0e-04
	wall			f	f	f	2.8e-05
Air Ejector Room	floor	55	56	f	5.6e+00	1.7e-06	7.8e-02
	wall			f	f	h	1.5e-03
Condenser Area	floor	19	<1	f	6.0e-03	5.7e-07	5.7e-04
	wall			f	f	h	h
Pipe Tunnel	floor	15	1.5	f	4.7e-03	1.1e-06	2.9e-04
	wall			f	f	1.4e-07	2.1e-05
Feed Pump Room	floor	<1 <sup>g</sup>	h	f	5.2e-04	f	8.4e-05
	wall			h	h	h	h
Seal Oil Room	floor	0.005 <sup>g</sup>	h	f	f	f	2.1e-05
	wall			h	h	h	h
Turbine Enclosure +27 ft elevation	floor	<1 <sup>g</sup>	h	f	3.1e-03	8.5e-07	1.2e-04
	wall			f	4.2e-03	2.8e-07	f
Turbine Washdown Area +27 ft elevation	floor	<1 <sup>g</sup>	h	f	1.0e-03	1.7e-06	6.1e-05
Hot Lab	floor	<1 <sup>g</sup>	h	f	1.2e-02	f	7.3e-05
Laundry/Demin Area +27 ft elevation	floor	<1 <sup>g</sup>	h	f	2.6e-03	4.3e-07	7.7e-05
Laundry/Hot Lab +34 ft elevation	floor	h	h	f	1.0e-03	f	2.0e-04

<sup>a</sup> Average values of PG&E survey conducted May 1984 unless otherwise specified

<sup>b</sup> Ion chamber

<sup>c</sup> Minimum sensitivity: alpha: 1E-4  $\mu\text{Ci}/100\text{cm}^2$   
 beta: Cutie Pie 5E-3  $\mu\text{Ci}/100\text{cm}^2$   
 HP-210 2E-6  $\mu\text{Ci}/100\text{cm}^2$

<sup>d</sup> Based on Cs-137

<sup>e</sup> Based on Sr-90 (10%), Co-60 (45%) and Cs-137 (45%)

<sup>f</sup> Not detected

<sup>g</sup> Previous survey

<sup>h</sup> Data not recorded

Table A-29. Inventory of Materials in a 1971-Vintage 1,000 MWe PWR Facility

Metal	Total Mass (t)
<b>Carbon Steel</b>	<b>3.3e+04</b>
Rebar	1.3e+04
All Other	2.0e+04
Stainless Steel	2.1e+03
Galvanized Iron	1.3e+03
Copper	6.9e+02
Inconel	1.2e+02
Lead	46
Bronze	25
Aluminum	18
Brass	10
Nickel	1.0
Silver	< 1.0

Source: Bryan and Dudley 1974

With regard to the steel inventories, there are two significant differences between a PWR and BWR. A BWR has less heat-transfer piping and lacks a steam generator, but has more extra-vessel primary components, including a pressure suppression chamber. A second difference is the estimated quantity of rebar used for concrete reinforcement. Of the 32,700 tons of carbon steel in the Reference 1,000 MWe PWR, Bryan and Dudley estimated that about 13,300 tons is rebar; for the 1,000 MWe Reference BWR, the total mass of rebar was estimated at 18,300 tons (Oak et al. 1980).

Although the amount of steel required to construct a BWR is only slightly greater than for a PWR, a greater fraction of the steel (and other metals) is contaminated. This is because primary-to-secondary leakage causes radioactive contamination of the BWR steam flow, which in turn contaminates turbine plant equipment; in a PWR, such equipment is usually uncontaminated.

Table A-31 identifies material estimates for a 1,000-MWe BWR plant. Material estimates for metals other than carbon and stainless steel for the 1,000-MWe Reference BWR are assumed to be identical to those of the 1,000-MWe Reference PWR.

Table A-30. Breakdown of Materials Used in PWR Plant Structures and Reactor Systems (t)

System	Carbon Steel	Stainless Steel	Galvanized Iron	Copper	Inconel	Lead	Bronze	Aluminum	Brass	Nickel	Silver
Structures/Site	16519.3	28.6	814.2	33.1	0	33.1	0.2	1.2	2.9	0.1	0.1
Site Improvements	1692.9	0.0	17.9	1.5	0.0	0.7	0.0	0.1	0.0	0.0	0.0
Reactor Building	7264.2	5.7	301.2	9.3	0.0	0.0	0.0	0.1	0.3	0.0	0.0
Turbine Building	3641.2	0.0	196.4	1.6	0.0	0.0	0.1	0.8	1.4	0.0	0.0
Intake/Discharge	333.7	0.0	3.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reactor Auxiliaries*	<u>1358.7</u>	<u>0.0</u>	<u>109.8</u>	<u>0.8</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.2</u>	<u>0.0</u>	<u>0.0</u>
Fuel Storage	<u>364.6</u>	<u>21.1</u>	<u>43.4</u>	<u>0.3</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.1</u>	<u>0.1</u>	<u>0.0</u>	<u>0.0</u>
Miscellaneous Bldgs.	1864	1.8	141.9	19.4	0.0	32.4	0.1	0.1	0.9	0.1	0.1
<b>Reactor Plant Equipment</b>	<b><u>3444.9</u></b>	<b><u>1154.6</u></b>	<b><u>5.5</u></b>	<b><u>50.4</u></b>	<b><u>124.1</u></b>	<b><u>4.5</u></b>	<b><u>0.5</u></b>	<b><u>5.2</u></b>	<b><u>0</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
Reactor Equipment	<u>430.0</u>	<u>275.1</u>	<u>0.0</u>	<u>6.8</u>	<u>124.1</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Main Heat Trans. System	<u>1686.5</u>	<u>202.5</u>	<u>1.6</u>	<u>9.8</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Safeguards Cool. System	<u>274.2</u>	<u>199.1</u>	<u>1.1</u>	<u>2.9</u>	<u>0.0</u>	<u>0.0</u>	<u>0.1</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Radwaste System	<u>35.2</u>	<u>31.9</u>	<u>0.8</u>	<u>0.2</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Fuel Handling System	<u>82.0</u>	<u>67.0</u>	<u>0.3</u>	<u>0.2</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Other Reactor Equipment	<u>823.5</u>	<u>230.3</u>	<u>1.7</u>	<u>1.5</u>	<u>0.0</u>	<u>4.5</u>	<u>0.4</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
Instrumentation & Control	<u>113.5</u>	<u>148.7</u>	<u>0.0</u>	<u>29.0</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>	<u>5.2</u>	<u>0.0</u>	<u>0.0</u>	<u>0.0</u>
<b>Turbine Plant Equipment</b>	<b><u>10958.3</u></b>	<b><u>883.2</u></b>	<b><u>4.7</u></b>	<b><u>51.4</u></b>	<b><u>0.0</u></b>	<b><u>0.0</u></b>	<b><u>21.5</u></b>	<b><u>1.2</u></b>	<b><u>6.9</u></b>	<b><u>0.0</u></b>	<b><u>0.0</u></b>
Turbine-Generator	4138.6	129.9	0.5	35.2	0.0	0.0	19.7	0.0	0.0	0.0	0.0
Heat Rejection Systems	2501.1	9.1	2.2	3.0	0.0	0.0	0.7	0.0	0.4	0.0	0.0
Condensing Systems	1359.8	392.3	0.6	1.3	0.0	0.0	0.3	0.0	1.5	0.0	0.0
Feed-Heating System	1367.7	221.2	0.5	1.2	0.0	0.0	0.3	0.0	3.9	0.0	0.0
Other Equipment	1541.3	89.4	0.9	0.7	0.0	0.0	0.5	0.0	1.1	0.0	0.0
Instrumentation & Control	49.8	41.3	0.0	10.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0
<b>Electric Plant Equipment</b>	<b><u>965.5</u></b>	<b><u>0.0</u></b>	<b><u>431</u></b>	<b><u>556.5</u></b>	<b><u>0.0</u></b>	<b><u>6.8</u></b>	<b><u>2.5</u></b>	<b><u>4.1</u></b>	<b><u>0.0</u></b>	<b><u>0.6</u></b>	<b><u>0.4</u></b>
Switchgear	30.4	0.0	1.4	2.8	0.0	0.0	0.7	0.0	0.0	0.0	0.3
Station Service Equip.	654.1	0.0	8.5	19.0	0.0	6.8	0.7	0.0	0.0	0.0	0.1
Switchboards	87.0	0.0	0.0	13.5	0.0	0.0	0.1	4.1	0.0	0.0	0.0
Protective Equipment	5.9	0.0	0.0	39.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Structures & Enclosure	112.5	0.0	421.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Power & Control Wiring	75.6	0.0	0.0	482.2	0.0	0.0	0.5	0.0	0.0	0.6	0.0
<b>Miscellaneous Equipment</b>	<b><u>843.2</u></b>	<b><u>13.7</u></b>	<b><u>2</u></b>	<b><u>2.6</u></b>	<b><u>0</u></b>	<b><u>2</u></b>	<b><u>0.4</u></b>	<b><u>6.5</u></b>	<b><u>0.3</u></b>	<b><u>0</u></b>	<b><u>0</u></b>
Transportation & Lifting	529.3	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air & Water Service Sys.	232.5	6.0	0.0	1.1	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Communications Equip.	4.7	0.0	0.6	1.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
Furnishings & Fixtures	76.7	7.7	1.4	0.0	0.0	2.0	0.4	6.1	0.0	0.0	0.0
<b>Entire Plant</b>	<b><u>32731.2</u></b>	<b><u>2080.1</u></b>	<b><u>1257.4</u></b>	<b><u>694</u></b>	<b><u>124.1</u></b>	<b><u>46.4</u></b>	<b><u>25.1</u></b>	<b><u>18.2</u></b>	<b><u>10.1</u></b>	<b><u>0.7</u></b>	<b><u>0.5</u></b>

Source: Bryan and Dudley 1974

\* Underlined text identifies equipment/systems with significant amounts of radioactive contamination.

Table A-31. Inventories of Ferrous Metals Used to Construct a 1,000-MWe BWR Facility

Metal	Total Mass (t)
<b>Carbon Steel</b>	<b>3.4e+04</b>
Rebar	1.8e+04
All Other	1.6e+04
Stainless Steel	2.1e+03

Source: Oak et al. 1980

## A.5 METAL INVENTORIES WITH THE POTENTIAL FOR CLEARANCE

From data presented in previous sections, two important conclusions can be stated: (1) only a fraction of metal inventories is likely to be significantly contaminated and (2) not all contaminated metal inventories are candidates for clearance. The potential for clearance is largely determined by the practicality and efficacy with which contaminated scrap can be decontaminated to an acceptable level.

The choice of available decontamination methods needed to make scrap metal candidates for clearance is largely dependent on the initial level of contamination, the type of surface, physical accessibility to the surface, the radionuclides involved and their chemical states, and the size and configuration of the metal object.

Several techniques are currently used in decontamination efforts at nuclear facilities. Their applicability, however, is not without restrictions and for nearly all approaches, there are numerous factors that affect their efficacy. Examples include the choice of cleaner/solvent/surfactant for hand wiping, the selection of chemical solvents for the dissolution and removal of radioactive corrosion films or base metal, or the innovative use of dry-ice (CO<sub>2</sub>) pellets for abrasive blasting. These techniques and their general applicability and limitations are briefly summarized below.

### **Hand Wiping**

Rags moistened with water or a solvent such as acetone can be an effective decontamination process. Wiping can be used extensively and effectively on smaller items with low-to-medium external contamination levels and easily accessible internal contamination. This method may not work well if the item is rusty or pitted. It requires access to all surfaces to be cleaned, is a relatively slow procedure, and its hands-on nature can lead to high personnel exposure. On the

positive side, wiping can provide a high decontamination factor (DF), generates easily handled decontamination wastes (contaminated rags), requires no special equipment, and can be used selectively on portions of the component.

### **Steam Cleaning**

This may be performed either remotely in a spray booth or directly by decontamination personnel using some type of hand-held wand arrangement. In the former case, only minimal internal decontamination is possible; however, reasonable external cleaning can be accomplished quickly while minimizing external exposure to direct radiation. Containment of the generated wastes and protection of personnel from radioactive contamination may be difficult, however.

### **Abrasive Blasting**

This is a highly effective procedure even for surfaces that are rusty or pitted. As with hand-held steam cleaning, this method suffers from internal accessibility problems. It also generates large amounts of solid wastes and, being a dry process, produces significant quantities of airborne radioactive dust. Abrasive blasting may be used if its high effectiveness can be justified after taking into account the radiation exposures, generation of radioactive waste and limited accessibility to internal surfaces. Some of the aforementioned disadvantages are obviated when dry ice pellets are used.

### **Hydrolasing**

The use of high pressure water jets for decontamination falls somewhere between steam cleaning and abrasive blasting in effectiveness. Less effective than abrasive blasting, it has the advantage of producing liquid wastes (that can be processed) rather than solid wastes. As an external cleaning technique, it has the advantage of reducing the generation airborne radioactive dusts, although this is offset by the potential of spreading contamination by splashing. The use of hydrolasing is generally limited to cases where access to internal surfaces is not required.

### **Ultrasonic Cleaning**

Since this is an immersion process that is limited to smaller items, it is generally unsuitable for large-scale decontamination. Although ultrasonic cleaning can be especially effective in removing contamination from crevices, it is doubtful that clearance levels can be reached consistently with this technique to make it a viable option.

## **Electropolishing**

This is an electrochemical process where the object to be decontaminated serves as the anode in an electrolytic cell and radioactive contamination on the item is removed by anodic dissolution of the surface material. Although it is a relatively new process and has not yet been used for a full scale decontamination operation, it nevertheless requires consideration as a technique on the basis of its superior effectiveness in cleaning almost any metallic surface to a completely contamination-free state. On the other hand, this process has several limitations including the size of contaminated objects, the cost of the electrolytes and special equipment, the consumption of considerable power and the production of highly radioactive solutions.

## **Chemical Decontamination**

Chemical flushing is recommended for remote decontamination of intact piping systems and their components. This technique uses concentrated or dilute solvents in contact with the contaminated item to dissolve either the contamination film covering the base metal or the base metal itself. Dissolution of the film is intended to be nondestructive to the base metal and is generally used for operating facilities. Dissolution of the base metal, however, can be considered in a decommissioning program where reuse of the item will not occur.

Based on starting levels of contamination and required decontamination efforts, scrap metal inventories at nuclear power plants can be grouped into four categories. A description of each of these categories appears below, followed by a list of examples of major components that, under normal operating conditions, are most likely to be grouped in that category.

1. **Low-level, surface-contaminated.** This category is likely to comprise components that may be removed from buildings with significant residual radionuclide inventories but involve systems that are completely isolated from primary coolant, coolant waste streams and other media with substantial levels of radioactivity. A sizeable fraction of scrap metal within this category will exhibit contamination that is limited to external surfaces and not exceed  $10^5$  dpm/100 cm<sup>2</sup>. Decontamination strategies are most likely to be routine with 100% success at achieving foreseeable clearance levels.
  - a. Structural metals in the turbine building, auxiliary building and support buildings
  - b. Control and instrumentation cables, cable trays
  - c. Mechanical systems/piping not associated with primary coolant and radwastes
2. **Medium-level, surface-contaminated.** Metal components in direct contact with media that are less contaminated than the primary coolant and liquid radwastes may have

internal and/or external surface contamination levels between  $10^5$  and  $10^7$  dpm/100 cm<sup>2</sup>. Scrap metal in this category requires substantial decontamination efforts with less than 100% success in achieving unrestricted release. Examples include:

- a. Containment spray recirculation systems
  - b. Most auxiliary support systems
  - c. BWR steam lines
  - d. BWR turbines
  - e. BWR condenser
  - f. Containment building crane, refueling equipment, etc.
  - g. Reactor building structural steel
  - h. Fuel storage pool liner and water cleanup system
3. **High-level surface-contaminated.** Scrap metal in this category will be represented by systems internally exposed to and contaminated by primary coolant and liquid radwastes leading to contamination levels in excess  $10^7$  dpm/100 cm<sup>2</sup>. Variable fractions of such metals are likely to be decontaminated to a level that permits unrestricted release.
- a. PWR primary recirculation piping
  - b. PWR primary pumps and valves
  - c. Liquid radwaste systems/tanks
  - d. PWR steam generators
  - e. Primary coolant cleanup system
  - f. PWR pressurizer
  - g. Coolant letdown and cleanup
  - h. Spent fuel pool cooling
4. **Volumetrically contaminated.** Components proximal to the reactor core may contain volumetrically distributed activation products that range from nominal to extremely high levels. (Some of these components may also have high levels of surface contamination.) Removal of volumetrically distributed contaminants by standard processes is not achievable.
- a. Reactor vessel
  - b. Reactor vessel top head

- c. Reactor vessel internals
- d. Control rod drive lines
- e. Reactor building components proximal to pressure vessel (< 10%)
- f. Rebar (~ 1% of plant total)

#### A.5.1 Contaminated Steel Components with the Potential for Clearance

The steel components and systems of the Reference BWR and PWR which are candidates for clearance are described in the following sections. (As discussed above, metals with significant levels of volumetrically distributed activation products would not be considered for clearance.) These tables in each of these sections list the system components and their corresponding masses. The materials composing the individual components have not been adequately defined. While a considerable number of components could be identified to consist exclusively of carbon steel or stainless steel, large quantities of steel exist as thick-walled carbon steel that is clad with thin-walled stainless steel (e.g., large piping, valves, vessels, tanks). When stainless steel provides corrosion resistant cladding, it is in effect physically inseparable from its large carbon steel component. In other instances, a given item will consist of many independent parts, each having a different composition. For example, a recirculation pump may have a carbon steel casing and base with stainless steel shaft, impellers and other internals. Although potentially separable, segregation of such individual components is labor intensive and may be precluded by considerations of worker exposures (and ALARA) and/or economic factors. A prudent approach may, therefore, be to assume that all steel scrap containing nickel be categorized as "stainless steel" (even if the nickel content is well below that of standard stainless steel alloys) because it is easier to upgrade scrap by adding nickel and other alloying material than it is to remove nickel for the production of mild steel or carbon steel.

##### A.5.1.1 Reference BWR

For the Reference BWR, a total of 29 contaminated systems are identified that are grouped by location (i.e., reactor building, radwaste building and turbine building). The systems in each building are listed in alphabetical order in Tables A-32 to A-60, together with the system-average level of contamination as previously defined on page A-45. Piping inventories for the Reference BWR have been quantified and segregated by plant location in Tables A-61 to A-64.

In total, it is estimated that about 8,400 t of contaminated steel from the Reference BWR are candidates for clearance. Based on material composition data cited by Oak et al. (1980), it is further estimated that of this total, stainless steel comprises nearly 1,700 t. Stainless steel that is physically bound to carbon steel, however, may not be readily segregated.

### Reference BWR Steel Inventories in the Reactor Building

Table A-32. Containment Instrument Air System

Number	Component	Mass (kg)	
		Each	Total
22	Instrument Air Accumulators	129	2,838
1	6" Check Valve	68	68
1	6" Valve	82	82
222	Valves (¾ - 2" dia.)	NA	4,008
<b>Total</b>			<b>6,996</b>

Note: System average contamination level = low

Table A-33. Control Rod Drive System

Number	Component	Mass (kg)	
		Each	Total
460	CRD Blade	182	83,720
225	CRD Mechanism	218	49,050
185	Direction Control Set	36	6,660
370	Scram Valve	32	11,840
210	Scram Accumulator	64	13,440
2	CRD Pump	1,816	3,632
2	Scram Discharge Volume	908	1,816
2	Pump Suction Filter	182	364
2	CRD Drive Water Filter	45	90
2,660	Valves (¾ - 4" dia.) & Components	NA	48,830
<b>Total</b>			<b>219,442</b>

Note: System average contamination level = 80% low; 20% medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-34. Equipment Drain Processing System

Number	Component	Mass (kg)	
		Each	Total
1	Waste Demineralizer	907	907
1	Waste Collector Filter	1,812	1,812
1	Waste Filter Hold Pump	318	318
1	Waste Collector Tank & Educator	10,229	10,229
1	Waste Collector Pump	284	284
1	Spent Resin Tank	657	657
1	Spent Resin Pump	102	102
1	Waste Surge Tank & Educator	18,282	18,282
1	Waste Surge Pump	284	284
2	Waste Sample Tank & Educator	6,960	13,920
2	Waste Sample Pump	230	462
199	Valves (1 - 8" dia.)	NA	5,374
<b>Total</b>			<b>52,631</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-35. Fuel Pool Cooling and Cleanup System

Number	Component	Mass (kg)	
		Each	Total
15	Spent Fuel Racks	18,424	276,360
1	Fuel Pool Liner	32,000	32,000
2	FPCC Pumps	527	1,054
2	FPCC Demineralizer	1,566	3,132
2	Skimmer Surge Tank	5,354	10,708
2	FPCC Heat Exchanger	2,038	4,076
1	Supp. Pool Cleanup Pump	527	527
2	Resin Tank Agitator	36	72
1	Fuel Pool Precoat Pump	284	284
1	(Precoat) Dust Evacuator	104	104
2	FPCC Hold Pump	195	390
1	FPCC Precoat Tank	227	227
1	FPCC Resin Tank	227	227
165	Valves (1 - 10" dia.) & Components	NA	8,038
<b>Total</b>			<b>337,199</b>

Note: System average contamination level = high

Table A-36. High Pressure Core Spray System

Number	Component	Mass (kg)	
		Each	Total
2	24" Suction Strainer	172	344
1	12 X 24" Pump	27,410	27,410
1	1 X 2" Pump	82	82
61	Valves (24 - ¾" dia.)	NA	18,459
<b>Total</b>			<b>46,295</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-37. HVAC Components System

Number	Component	Mass (kg)	
		Each	Total
7	Containment Recirculation Fans	636	4,452
5	Containment Fan Coil Units	1,500	7,500
17	Emergency Fan Foil Units	955	16,235
NA	Ducts (750 linear meters)	NA	29,975
<b>Total</b>			<b>58,162</b>

Note: System average contamination level = low

Table A-38. Low Pressure Core Spray System

Number	Component	Mass (kg)	
		Each	Total
2	24" Suction Strainer	172	344
1	Vent Strainer	43	43
1	14 X 24" Pump	9,625	9,625
1	Pump Pit	182	182
1	1 X 2" Pump	82	82
45	Valves (¾ - 24" dia.)	NA	10,523
<b>Total</b>			<b>20,799</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-39. Main Steam System

Number	Component	Mass (kg)	
		Each	Total
1	HP Turbine	194,169	194,169
2	LP Turbine	371,130	742,260
2	RFW Turbine	18,160	36,320
2	Steam Chest	55,565	111,130
1	Gland Steam Condenser	1,861	1,816
2	Ejector Condenser	1,816	3,632
1	Moisture Separator	908	908
1	Bypass Valve Assy.	5,266	5,266
2	Moisture Separator Reheater	208,386	416,772
2	Steam Evaporator	13,472	26,944
4	2" Strainer	43	172
2	4" Strainer	100	200
2	12 Stop Check	894	1,788
4	30" Flow Restrictor	1,362	5,448
18	8" AO SRV	921	16,578
36	10" Vacuum Breakers	408	14,724
18	24 x 12" Quenchers	749	13,482
1	72" MOV	51,900	51,900
6	Stop Valves	18,160	108,960
6	Interceptor Valves	4,540	27,240
8	30" MSIV	636	5,088
1	24" MOV	3,223	3,223
4	24" Relief Valve	4,190	16,760
2	20" Relief Valve	3,496	6,992
1	16" MOV	1,920	1,920
2	16" Check Valve	1,534	3,068
2	14" Check Valve	1,008	2,016
2	14" MOV	1,253	2,506
2	12" MOV	1,135	2,270
8	28" HOV Governor Valves	3,632	29,056
951	Valves (1 - 10" dia.)	NA	69,592
<b>Total</b>			<b>1,922,200</b>

Note: System average contamination level = 60% medium; 40% low

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-40. Main Steam Leakage Control System

Number	Component	Mass (kg)	
		Each	Total
8	½" Valve	11	88
28	¾" Valve	14	392
2	1" Flow Element	17	34
14	1" Valve	23	322
4	1" Check Valve	17	68
4	1-½" Flow Element	21	84
20	1-½" MOV	23	460
2	1-½" Check Valve	21	42
2	MSLC Fan (3")	204	408
4	MSLC Heater	57	227
<b>Total</b>			<b>2,125</b>

Note: System average contamination level = low

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-41. Miscellaneous Items from Partial System

Number	Component	Mass (kg)	
		Each	Total
5	TIP Drive Unit	361	1,805
2	TIP Indexing Unit	9	72
5	TIP Ball Valve	23	115
5	Explosive Shear Valve	23	115
5	TIP Shield Pig	154	770
1 set	TIP Tubing	295	295
2	Hogger (mechanical vacuum pump)	3,171	6,342
1	Refueling Bridge	24,918	24,918
1	Reactor Service Platform	5,210	5,210
2	Refueling Mast	295	590
1	CRD Removal Turntable	2,492	2,492
1	CRD Removal Trolley	173	173
1	Incore Instrument Grapple	36	36
1	Fuel Support Piece Grapple	41	41
1	Control Blade Grapple	59	59
1	Spent Fuel Pool Work Table	445	445
2	Fuel Prep Machine	381	762
1	Channel Measurement Machine	422	422
185	Blade Guide	73	13,505
1	In Core Instrument Strongback	100	100
1	Manipulators, crows feet, etc.	136	136
20	In-vessel Manipulator Poles	14	280
9	Drywell Recirculation Fan	254	2,286
4	Stud Tensioner	1,044	4,176
1	RPV Head Strongback	2,134	2,134
1	Dryer/Separator Strongback	60	60
<b>Total</b>			<b>67,339</b>

Note: System average contamination level = 55% low; 45% medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-42. Reactor Building, Closed Cooling Water System

Number	Component	Mass (kg)	
		Each	Total
3	RBCCW Heat Exchanger	7,460	22,380
2	RBCCW Pump	1,597	3,194
1	RBCCW Surge Tank	531	531
5	Drywell Cooler & Fans	745	3,725
1	14" MOV	449	449
3	12" Valve	331	993
7	10" MOV	250	1,750
6	10" Valve	250	1,500
4	10" Check Valve	168	672
1	10" Flow Element	16	672
218	Valves (¾ - 8" dia.)	NA	6455
<b>Total</b>			<b>42,321</b>

Note: System average contamination level = low

Table A-43. Reactor Building Equipment and Floor Drains System

Number	Component	Mass (kg)	
		Each	Total
4	Drain Sump Pump	523	2,908
3	Drain Sump Pump	650	1,950
1	Equipment Drain Heat Exchanger	680	680
1	Drywell Equipment Drain HX	680	680
97	Valves (¾ - 6" dia.)	NA	3,725
<b>Total</b>			<b>9,943</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-44. Reactor Core Isolation Cooling System

Number	Component	Mass (kg)	
		Each	Total
1	Pelton Wheel Turbine/Pump	6,260	6,260
1	Barometric Condenser	553	553
1	Condenser Pump	679	679
1	Water Leg Pump	216	216
1	Vacuum Pump	453	453
1	Vacuum Tank	407	407
1	Steam Condensate Drip Pot	109	109
2	8" Suction Strainers	66	112
4	¾" Steam Trap	25	100
1	10" Exhaust Drip Chamber	309	309
1	Turbine Exhaust Sparer	241	241
284	Valves (¾ - 10" dia.)	NA	12,115
<b>Total</b>			<b>21,554</b>

Note: System average contamination level = medium

Table A-45. Reactor Coolant Cleanup System

Number	Component	Mass (kg)	
		Each	Total
2	RWCU Pump	590	1,180
2	Clean Up Hold Pump	534	1,068
1	Clean Up Precoat Pump	454	454
1	Sludge Discharge Pump	284	284
1	Decant Pump	102	102
2	Non-regenerative HX	4,086	8,172
3	Regenerative HX	4,131	12,394
2	Filter Demineralizer	3,178	6,356
1	Batch Tank	227	227
2	Phase Separator Tank	2,043	4,086
1	Precoat Agitator	27	27
259	Valves (½ - 6" dia.)	NA	13,170
<b>Total</b>			<b>47,520</b>

Note: System average contamination level = high

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-46. Residual Heat Removal System

Number	Component	Mass (kg)	
		Each	Total
3	RHR Pump	7,792	23,376
1	Water Leg Pump	397	397
1	Drywell Upper Spray Ring Header	8,562	8,562
1	Drywell Lower Spray Ring Header	13,063	13,063
1	Wetwell Spray Ring Header	5,347	5,347
6	Suppression Pool Suction Strainers	195	1,171
2	RHR Heat Exchanger	29,190	58,380
3	24" MOV	7,150	21,450
2	20" MOV	4,086	8,172
1	20" Valve	4,086	4,086
11	18" MOV	4,603	50,633
8	18" Valve	4,603	36,828
5	18" Check	2,762	13,810
3	18" Flow Element	2,762	8,286
2	18" Restricting Orifice	2,762	5,524
4	16" MOV	2,724	10,896
4	14" MOV	1,544	6,176
2	14" Valve	1,544	3,088
3	14" Air Operated Check	971	2,913
2	14" Restricting Orifice	944	1,888
3	12" MOV	1,017	3,051
3	12" Valve	1,017	3,051
3	12" Air Operated Check	581	1,743
1	12" Restricting Orifice	549	549
2	10" Valve	731	1,462
1	10" Check Valve	399	399
324	Valves (¾ - 3" dia.)	NA	12,100
<b>Total</b>			<b>306,401</b>

Note: System average contamination level = low

**Reference BWR Steel Inventories in the Reactor Building (continued)**

Table A-47. Miscellaneous Drains System

Number	Component	Mass (kg)	
		Each	Total
1	Misc. Drain Tank #1	487	487
1	Misc. Drain Tank #2 with Pumps	654	654
174	Valves (1" - 6" dia.)	NA	6,509
Total			7,650

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Radwaste Building**

Table A-48. Chemical Waste Processing System

Number	Component	Mass (kg)	
		Each	Total
2	Chemical Waste Tank	5,024	10,048
2	Detergent Drain Tank	1,834	3,668
2	Detergent Drain Pump	175	350
2	Concentrator Feed Pump	254	508
2	Chemical Waste Pump	478	956
1	Detergent Drain Filter	1,133	1,133
2	Chemical Addition Pump	257	454
2	Tank Agitators	36	72
2	Chemical Addition Pump	175	350
2	Distillate Tank	5,024	10,048
2	Distillate Tank Pump	230	460
1	Distillate Polishing Demineralizer	454	454
2	Decon Solution Concentrator	3,405	6,810
2	Decon Sol. Concentrator Tank	711	1,422
2	Decon Conc. Recycle Pump	843	1,686
2	Decon Concentrator Condenser	2,305	4,610
2	Decon Concentrator Pre Heater	3,143	6,286
1	Decon Concentrator Waste Pump	254	508
2	Chemical Waste Stream Mixer	111	222
2	Condensate Receiver Tank	950	1,900
2	Condensate Receiver Tank Pump	102	204
293	Valves (1" - 8" dia.)	NA	7,654
<b>Total</b>			<b>59,803</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Radwaste Building (continued)**

Table A-49. Condensate Demineralizers System

Number	Component	Mass (kg)	
		Each	Total
6	Filter Demineralizers	5,300	31,800
6	Resin Trap (with Basket)	953	5,718
6	Demin Hold Pump	159	954
1	Condensate Backwash Receiving Tank	6,912	6,912
1	Sludge Disc Mixing Pump	420	420
1	Condensate Decant Pump	420	420
1	Condensate Backwash Transfer Pump	420	420
2	Condensate Phase Separator Tank	3,178	6,356
363	Valves & Components (1 - 36")	NA	36,783
<b>Total</b>			<b>89,783</b>

Note: System average contamination level = medium

Table A-50. HVAC Components System

Number	Component	Mass (kg)	
		Each	Total
11	Radwaste Air Handlers	1,327	14,597
3	Filter Units and Fans	11,123	33,369
NA	Ducts (1,980 linear meters)	NA	54,785
<b>Total</b>			<b>102,751</b>

Note: System average contamination level = low

**Reference BWR Steel Inventories in the Radwaste Building (continued)**

Table A-51. Radioactive Floor Drain Processing System

Number	Component	Mass (kg)	
		Each	Total
1	Floor Drain Demineralizer	907	907
1	Floor Drain Sample Tank	6,960	6,960
1	Floor Drain Sample Pump	230	230
1	Floor Drain Filter Aid Pump	118	118
1	Floor Drain Filter Hold Pump	317	317
1	Floor Drain Filter	1,812	1,812
1	Floor Drain Collector Pump	284	284
1	Floor Drain Collector Tank	10,229	10,229
1	Waste Decant Pump	102	102
1	Waste Sludge Discharge Mixing Pump	288	288
1	Waste Sludge Phase Sep. Tank	5,490	5,490
171	Valves (½ - 8" dia.)	NA	4,500
<b>Total</b>			<b>31,237</b>

Note: System average contamination level = medium

Table A-52. Rad Waste Building Drains System

Number	Component	Mass (kg)	
		Each	Total
1	Chemical Drain Sump Pump	666	666
2	EDR Sump Pump	585	1,170
3	FDR Sump Pump	483	1,449
38	Valves & Components (¾ - 3" dia.)	NA	612
<b>Total</b>			<b>3,897</b>

Note: System average contamination level = high

**Reference BWR Steel Inventories in the Radwaste Building (continued)**

Table A-53. Standby Gas Treatment System

Number	Component	Mass (kg)	
		Each	Total
42	2" Check Valve	25	1,050
2	18" Valves	2,225	4,450
14	18" Damper, MOV	563	7,882
2	18" Damper, AOV	563	1,126
2	SGT Filter Unit	8,898	17,796
8	¾" Valve	14	112
4	Blower	2,043	8,172
<b>Total</b>			<b>40,588</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Turbine Building**

Table A-54. Feed and Condensate System

Number	Component	Mass (kg)	
		Each	Total
2	Turbine and Feed Pump	54,821	109,642
3	Condensate Booster Pump	12,006	36,018
3	Condensate Pump	21,883	65,649
1	Gland Exhaust Condenser	4,032	4,032
2	Air Ejector Condenser & Ejectors	6,614	13,228
1	Off Gas Condenser	897	897
2	#6 Feedwater Heater	73,394	146,788
2	#5 Feedwater Heater	68,863	137,726
3	#4 Feedwater Heater	35,338	106,014
3	#3 Feedwater Heater	50,288	150,864
3	#2 Feedwater Heater	51,194	153,582
3	#1 Feedwater Heater	62,974	188,922
2	Condensate Storage Tanks	50,475	100,950
2	Seal Steam Evaporator	13,451	26,902
2	Seal Steam Evaporator Blowdown Cooler	213	426
407	Valves (½ - 24" dia.)	NA	350,478
<b>Total</b>			<b>1,592,118</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Turbine Building (continued)**

Table A-55. Extraction Steam System

Number	Component	Mass (kg)	
		Each	Total
6	24" MOV	3,223	19,338
6	24" Stop Check	2,583	15,498
10	20" MOV	2,633	26,330
10	20" Stop Check	2,107	21,070
5	18" MOV	2,225	11,125
5	18" Stop Check	1,780	8,900
2	16" MOV	1,920	3,840
2	16" Stop Check	1,536	3,072
6	8" AOV	511	3,066
4	6" MOV	267	1,068
4	4" AOV	122	488
10	2" AOV	34	340
12	2" Restricting Orifice	25	300
85	Inst. Root (typ. ¾" globe)	15	1,275
<b>Total</b>			<b>115,710</b>

Note: System average contamination level = medium

Table A-56. Heater Vents and Drains System

Number	Component	Mass (kg)	
		Each	Total
2	Steam Evaporator Drain Tank	898	1,796
2	Heater Drain Tank	6,274	12,548
2	Moisture Separator Drain Tank	1,715	3,430
4	Reheater Drain Tank	1,134	4,536
4	Reheater Drain Tank	6,274	25,096
841	Valves & Components (1-½ - 20" dia.)	NA	151,369
<b>Total</b>			<b>198,775</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Turbine Building (continued)**

Table A-57. HVAC Components System

Number	Component	Mass (kg)	
		Each	Total
4	Exhaust Air Units	4,900	19,600
1	Standby Gas Treatment	8,853	8,853
10	Air Handlers & Filter Units	829	8,290
NA	Ducts (1,000 linear meters)	NA	48,503
<b>Total</b>			<b>85,246</b>

Note: System average contamination level = low

Table A-58. Offgas (Augmented) System

Number	Component	Mass (kg)	
		Each	Total
2	Catalytic Recombiner Vessel	453	906
2	Preheater Heat Exchanger	538	1,076
1	Offgas Condenser	897	897
1	Water Separator	271	271
2	Lab Vacuum Pump	45	90
2	Lab Vacuum Pump	45	90
2	Water Separator	1,359	1,718
8	Charcoal Ads. Vessel	4,077	32,615
2	Cooler Condenser	906	1,812
2	Pre-filter Vessel	1,133	2,266
2	After-filter Vessel	1,133	2,266
4	Desiccant Dryers	622	2,488
2	Dryer Heater	3,625	7,250
2	Dryer Chiller	2,265	4,530
2	Regenerator Blower	636	1,272
9	6" Air Operated Valve	82	738
18	6" Valve	82	1,476
175	Valves (¾ - 4" dia.)	NA	2,722
<b>Total</b>			<b>64,483</b>

Note: System average contamination level = medium

**Reference BWR Steel Inventories in the Turbine Building (continued)**

Table A-59. Recirculation System

Number	Component	Mass (kg)	
		Each	Total
2	Recirculation Pump with Motor	43,617	87,234
2	24" HOV	4,767	9,534
4	24" MOV	4,767	19,068
258	Valves (¾ - 2" dia.)	NA	4,700
<b>Total</b>			<b>120,536</b>

Note: System average contamination level = low

Table A-60. Turbine Building Drains System

Number	Component	Mass (kg)	
		Each	Total
4	Equipment Drain Sump Pump	586	2,344
4	Floor Drain Sump Pump	484	1,936
25	Small Valves (2 - 3" dia.)	NA	450
<b>Total</b>			<b>4,730</b>

Note: System average contamination level = medium

## Reference BWR Piping Inventories

Table A-61. Reactor Building

Piping Material	Outside Diameter (mm)						
	<60	73 - 254	305 - 406	457 - 610	660 - 762	914 - 1,829	Total
<b>Carbon Steel</b>							
Length (m)	2,323	3,922	505	952	55	—	
Mass (kg)	8,479	110,368	61,897	127,160	14,850	—	322,754
<b>Stainless Steel</b>							
Length (m)	6,169	500	54	—	—	—	
Mass (kg)	18,674	4,551	2,143	—	—	—	25,368
Total Mass (kg)							348,122

Note: average contamination level: medium

Table A-62. Primary Containment

Piping Material	Outside Diameter (mm)						
	<60	73 - 254	305 - 406	457 - 610	660 - 762	914 - 1,829	Total
<b>Carbon Steel</b>							
Length (m)	263	1,084	211	1,239	374	559	
Mass (kg)	1,366	63,181	29,760	554,877	145,312	234,882	1,029,378
<b>Stainless Steel</b>							
Length (m)	3,850	110	64	55	—	—	
Mass (kg)	10,603	3,411	8,789	21,440	—	—	44,243
Total Mass (kg)							1,073,621

Note: average contamination level: high

**Reference BWR Piping Inventories (continued)**

Table A-63. Turbine Building

Piping Material	Outside Diameter (mm)						
	<60	73 - 254	305 - 406	457 - 610	660 - 762	914 - 1,829	Total
<b>Carbon Steel</b>							
Length (m)	3,336	2,632	1,647	1,832	465	559	
Mass (kg)	14,153	115,525	176,600	386,321	240,698	234,882	1,168,179
<b>Stainless Steel</b>							
Length (m)	—	38	103	—	—	—	
Mass (kg)	—	1,474	6,421	—	—	—	7,895
Total Mass (kg)							1,176,074

Note: average contamination level: low

Table A-64. Radwaste and Control Buildings

Piping Material	Outside Diameter (mm)						
	<60	73 - 254	305 - 406	457 - 610	660 - 762	914 - 1,829	Total
<b>Carbon Steel</b>							
Length (m)	3,087	3,337	338	12	—	99	
Mass (kg)	10,267	75,778	29,221	4,584	—	29,410	149,260
<b>Stainless Steel</b>							
Length (m)	1,150	1,026	55	—	—	—	
Mass (kg)	4,747	10,164	1,756	—	—	—	16,667
Total Mass (kg)							165,927

Note: average contamination level: high

#### A.5.1.2 Reference PWR

Tables A-65 to A-79 list major contaminated PWR components by function and location. The total inventory of contaminated steel (excluding the reactor pressure vessel and its internals) is estimated at about 4,100 t. It should be pointed out, however, that about 2,000 t comprise primary system components that include steam generators, pressurizer, reactor coolant piping, etc. (see Table A-66). The long-term buildup of activated corrosion products and fission products on internal surfaces among these components is projected to be high. Even with intense and aggressive decontamination efforts, the free release of these components may not be technically achievable.

The balance of about 2,100 t includes 11 internally contaminated reactor support systems and piping that are associated with the Auxiliary Building/Fuel Storage facility and a variety of structural components where contamination is limited to external surfaces. It is estimated that nearly 20% of all of this metal is stainless steel.

#### Reference PWR Steel Inventories in the Reactor Building

Table A-65. External Surface Structures Equipment System

Component	Mass (kg)
Refueling Cavity Liner	17,000
Base Liner	54,000
Reactor Cavity Liner	14,500
Floor and Cavity Liner Plates	139,000
CRD Missile Shield	11,000
Stairways/Gratings	45,000
Miscellaneous Equipment	13,600
Total	294,100

Note: System average contamination level = 70% low; 30% medium

**Reference PWR Steel Inventories in the Reactor Building (continued)**

Table A-66. Internally Contaminated Primary System Components System

Number	Component			Mass (kg)	
				Each	Total
4	Steam Generator			312,000	1,248,000
4	Rx Coolant Pumps			85,350	341,400
1	Pressurizer			88,530	88,530
NA	Containment Spray Piping				90,800
1	Pressurizer Relief Tank			12,338	12,338
4	Safety Injection System Accumulator			34,700	138,800
1	Reactor Cavity Drain Pump			363	363
2	Containment Sump Pump			635	1,270
1	Excess Letdown Heat Exchanger			726	726
1	Regenerative Heat Exchanger			2,994	2,994
Reactor Coolant Piping					
Size	686 - 787 ID	Length	81		100,698
(mm)	51 - 356 OD		(m)	677	
Total					2,037,712

Note: System average contamination level = high

**Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings**

Table A-67. Component Cooling Water System

Number	Component			Mass (kg)	
				Each	Total
2	CCW Heat Exchanger			31,780	63,560
2	CCW Pump			6,810	13,620
1	CCW Surge Tank			908	1,816
1	Chem. Addition Tank			477	954
9	Sample Heat Exchanger			3,178	28,602
169	Valves (¾ - 24" dia.)				104,700
Total					213,252

Note: System average contamination level = low

Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)

Table A-68. Containment Spray System

Number	Component	Mass (kg)	
		Each	Total
2	Pump	3,087	6,174
2	Pump	45	90
1	Tank	2,490	2,490
6	Small Electrical Equipment	34	204
6	Large Electrical Equipment	68	408
46	Valves (¾ - 18" dia.)	NA	37,875
Total			47,241

Note: System average contamination level = medium

Table A-69. Clean Radioactive Waste Treatment System

Number	Component	Mass (kg)	
		Each	Total
1	Rx Coolant Drain Tank	758	758
2	Rx Coolant Drain Pump	227	454
1	Rx Coolant Drain Filter	159	159
1	Spent Resin Storage Tank	3,087	3,087
2	Clean Waste Receiving Tank	4,975	9,950
2	Clean Waste Receiving Pump	227	454
2	Treated Waste Monitor Tank	5,085	10,170
2	Treated Waste Monitor Pump	104	208
1	Aux. Building Drain Tank	949	949
2	Aux. Building Drain Pump	590	1,180
1	Chem. Waste Drain Tank	2,452	2,452
2	Chem. Waste Drain Pump	91	182
1	Waste Conc. Hold Tank	949	949
1	Waste Conc. Hold Pump	104	104
1	Clean Waste Filter	30	30
1	Clean Radwaste Evaporator	18,160	18,160
83	Valves (2 - 3" dia.)	NA	3,935
Total			53,181

Note: System average contamination level = medium

**Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)**

Table A-70. Control Rod Drive System

Number	Component	Mass (kg)	
		Each	Total
4	Small Electric Equipment	34	136
4	Large Electric Equipment	68	272
1	Large Mech. Equipment	68	68
<b>Total</b>			<b>476</b>

Note: System average contamination level = low

Table A-71. Electrical Components and Annunciators System

Number	Component	Mass (kg)	
		Each	Total
2	125 VDC Power (Small)	68	136
2	125 VDC Power (Medium)	227	454
1	125 VDC Power (Large)	2,270	2,270
1	4.16 kV AC & Aux. (Small)	227	227
1	4.16 kV AC & Aux. (Large)	9,080	9,080
7	480 kV AC Ld Cntr (Small)	227	1,589
7	480 kV AC Ld Cntr (Large)	908	6,356
1	480 kV AC MCC	227	227
12	480 kV AC MCC	9,080	108,960
2	Annunciators (Elec. Port.)	34	68
22	Annunciators (Mech. Port.)	34	748
<b>Total</b>			<b>130,115</b>

Note: System average contamination level = low

Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)

Table A-72. Chemical and Volume Control System

Number	Component	Mass (kg)	
		Each	Total
3	Regenerative Heat Exchanger	2,724	8,172
1	Seal Water Heat Exchanger	772	772
1	Letdown Heat Exchanger	863	863
1	Excess Letdown Heat Exchanger	726	726
2	Centrifugal Charge Pump	7,759	15,518
1	Volume Control Tank	2,202	2,202
3	Holdup Tank	13,620	40,860
2	Monitor Tank	9,080	18,160
2	Boric Acid Tank	9,080	18,160
1	Batch Tank	658	658
1	Resin Fill Tank	118	118
1	Reciprocal Charge Pump	8,036	8,036
2	Boric Acid Pump	281	562
1	Reactor Coolant Filter	91	91
2	Mixed Bed Demineralizer	477	954
1	Cation Ion Exchange	477	477
2	Seal Injection Filter	749	1,498
1	Concentrate Hold Tank	1,589	1,589
3	Evaporator Feed Ion Exchange	477	1,431
2	Evaporator Condensate Ion Exchange	477	954
2	Condensate Filter	18	18
1	Concentrates Filter	18	18
1	Conc. Hold Tank Transfer Pump	91	182
2	Gas Stripper Feed Pump	227	454
2	Boric Acid Evaporator Skid Assembly	9,489	18,978
1	Ion Exchange Filter	68	68
1	Recirculation Pump	288	288
378	Valves (¾ - 6" dia.)	NA	17,481
Total			159,288

Note: System average contamination level = high

Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)

Table A-73. Dirty Radioactive Waste Treatment System

Number	Component	Mass (kg)	
		Each	Total
1	Rx Cavity Drain Pump	363	363
2	Rx Cont. Sump Pump	681	1,362
1	Dirty Waste Monitor Tank	2,633	2,633
2	Dirty Waste Monitor Tank Pump	91	182
1	Dirty Waste Drain Tank	2,969	2,969
2	Dirty Waste Drain Tank Pump	181	362
2	Aux Building Sump Pump	590	1,180
46	Valves (2 -3" dia.)	NA	2,280
Total			11,331

Note: System-average contamination level = medium

Table A-74. Radioactive Gaseous Waste System

Number	Component	Mass (kg)	
		Each	Total
1	Surge Tank	404	404
4	Decay Tank	4,900	19,600
2	Gas Compressor	3,632	7,264
2	Moisture Separator	45	90
2	HEPA Prefilter	91	182
1	Exhaust Fan	45	45
2	Br. Seal Water Heat Exchanger	3,496	6,992
4	Large Electrical Equipment	68	272
2	Large Mechanical Equipment	2,270	4,540
1	HVAC Equipment	68	68
83	Valves (¾ - 4" dia.)	NA	4,607
Total			44,064

Note: System-average contamination level = medium

Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)

Table A-75. Residual Heat Removal System

Number	Component	Mass (kg)	
		Each	Total
2	Pump	3,087	6,174
2	Heat Exchanger Unit	10,487	20,974
12	Small Electrical Equipment	34	408
11	Large Electrical Equipment	68	748
1	Small Mechanical Equipment	34	34
42	Valves (3/8 - 14" dia.)	NA	49,032
Total			77,370

Note: System-average contamination level = high

Table A-76. Safety Injection System

Number	Component	Mass (kg)	
		Each	Total
4	Accumulator Tank	34,731	138,924
1	B. Injection Tank	12,939	12,939
2	Safety Injection Pump	3,904	7,808
1	Refueling Water Tank	80,721	80,721
1	Primary Water Storage Tank	45,037	45,037
10	Small Electrical Equipment	34	340
10	Large Electrical Equipment	68	680
1	Small Mechanical Equipment	34	34
89	Valves (¾ - 10" dia.)	NA	12,114
Total			298,597

Note: System-average contamination level = medium

Reference PWR Steel Inventories in the Auxiliary and Fuel Storage Buildings (continued)

Table A-77. Spent Fuel System

Number	Component	Mass (kg)	
		Each	Total
1	Pump	454	454
2	Pump	409	918
1	Pump	318	318
2	Filter	163	326
1	Filter	68	68
1	Demineralizer	998	998
2	Heat Exchanger	2,769	5,538
53	Valves (¾ - 10" dia.)	NA	14,117
1	Fuel Pool Liner	37,000	37,000
	Fuel Storage Racks		49,079
	Fuel Handling System		18,470
	Overhead Crane		113,000
Total			240,286

Note: System-average contamination level = high

Table A-78. Structural Steel Components

Number	Component	Mass (kg)	
		Each	Total
NA	Wall Support	NA	24,200
NA	Roof Support	NA	16,300
NA	Stairs/Grates/Tracks/Hand-rails	NA	33,200
NA	I-beams	NA	207,000
NA	HVAC Ducts	NA	26,550
NA	HVAC Components	NA	76,500
Total			383,750

Note: System-average contamination level = low

Table A-79. Reference PWR Non-RCS Stainless Steel Piping

Nominal I.D. (in.)	Schedule	I.D. (in.)	Length (m)	Inside Area (m <sup>2</sup> )	Mass (kg)
½	80	0.546	122	5.315	198
	160	0.464	122	4.517	238
¾	40	0.824	122	8.022	205
	80	0.742	183	10.84	400
	160	0.612	580	28.32	1,671
1	40	1.049	61	5.106	152
	80	0.957	61	4.658	590
	160	0.815	427	27.77	1,803
1½	40	1.610	122	15.67	493
	80	1.500	335	40.10	1,810
	160	1.338	549	58.62	3,967
2	40	2.067	305	50.31	1,655
	80	1.939	488	75.51	3,642
	160	1.687	1,067	143.6	11,840
3	160	2.624	140	29.31	2,985
4	160	3.438	183	50.2	6,128
6	160	5.187	311	128.7	20,972
8	160	6.813	143	77.7	15,923
10	140	8.500	192	130	29,750
12	140	10.126	88	71.1	18,370
14	140	11.188	100	89.3	24,474
Total				1055	147,266

Source: Smith et al. 1978, vol. 2, Table C.4-4

Notes: Includes piping for the following systems: residual heat removal, chem and volume control, emergency core cooling, containment spray, auxiliary feedwater, spent fuel pool cooling, condensate facility, station service, component cooling, service cooling, makeup water system.

Contamination levels vary over several orders of magnitude from near background levels to 10<sup>7</sup> dpm/100 cm<sup>2</sup>. About 80% is assumed to be low-level contaminated with the remaining 20% medium-level.

### A.5.1.3 Summary of Steel Inventories of the Reference Reactors

Table A-80 presents a summary of steel inventories of the reference reactors—the rebar data is copied from Tables A-29 and A-31. Estimates of the contaminated steel inventories (comprising

both carbon and stainless steels) of the Reference BWR and PWR were derived by summing the masses of the components listed in Tables A-32 to A-64 and A-65 to A-79, respectively. Estimates of the stainless steel portions of these steel inventories were developed from information provided by Bryan and Dudley (1974), Oak et al. (1980) and Smith et al. (1978). These data were used to construct Table A-30, which presents a breakdown of the stainless steel used to construct a Reference PWR—the radioactively contaminated components are underlined. This table shows that 1,155 t of stainless steel in reactor plant equipment and 21 t in spent fuel storage were contaminated, for a total of about 1,176 t, as listed in Table A-80. Included in this total, however, is about 348 t that is neutron activated at levels that would preclude the metal being cleared. Consequently, the releasable stainless steel inventory is about 828 t. Subtracting this from the total mass of 4,138 t of contaminated steel—the sum of the components listed in Tables A-65 to A-79—results in 3,310 t of contaminated, releasable carbon steel. The carbon and stainless steel inventories for the two metals with the three levels of contamination—shown in Table A-80—were derived, assuming that the low-, medium- and high-level contaminated components all contain the same proportions of carbon and stainless steel.<sup>3</sup>

Table A-80. Summary of Reference PWR and BWR Steel Inventories (t)

	PWR			BWR		
	All Steel	Carbon Steel	Stainless	All Steel	Carbon Steel	Stainless
Rebar		13,000			18,000	
All Other		19,731			16,000	
Total	34,811	32,731	2,080	36,100	34,000	2,100
Potentially Releasable <sup>a</sup>	4,138	3,310	828	8,442	6,753	1,689
Low-level <sup>b</sup>	1,051	841	210	2,882	2,306	576
Medium-level <sup>c</sup>	572	458	114	3,932	3,145	786
High-level <sup>d</sup>	2,515	2,012	503	1,628	1,302	326
Total Contaminated			1,176			
Volumetric		864	348			

<sup>a</sup> Contaminated steel that can be potentially decontaminated to meet foreseeable clearance standards

<sup>b</sup>  $<10^5$  dpm/100 cm<sup>2</sup>

<sup>c</sup>  $10^5$  —  $10^7$  dpm/100 cm<sup>2</sup>

<sup>d</sup>  $>10^7$  dpm/100 cm<sup>2</sup>

<sup>3</sup> The values displayed in this and other tables in this appendix are rounded; consequently, there may appear to be slight disparities in the totals shown.

The row marked “Total” lists the total quantities of steel used to construct each plant. “Releasable” refers to all contaminated steel that is a candidate for release, excluding only steel that is neutron-activated. (This includes metal that would require very aggressive decontamination methods to achieve any foreseeable clearance criteria.) The total mass of releasable, contaminated steel from the Reference BWR—the sum of the components listed in Tables A-32 to A-64—is 8,442 t. The carbon and stainless steel inventories for the BWR shown in Table A-80 were estimated assuming the same ratio of carbon steel to stainless as in the PWR<sup>4</sup>.

#### A.5.2 Applicability of Reference Reactor Data to the Nuclear Industry

The material inventories cited by Bryan and Dudley (1974) can be applied to other U.S. nuclear power plants; however, these inventories must be adjusted for the characteristics of individual plants, and the limitations inherent in this procedure must be acknowledged. The current U.S. nuclear power plant inventory comprises not only different designs but also varied power ratings. Nuclear power plant designs reflect standards for plant safety and the protection of the environment that have evolved over four decades. For example, Bryan and Dudley's reference plant used run-of-river cooling, which is not applicable to more recent nuclear facilities that employ cooling towers of various designs, holding ponds, sprays, etc. Significant quantities of materials are involved in some of these alternative cooling systems. Additionally, the 1979 accident at Three Mile Island mandated revised safety standards, which have added to the material inventory of more recent nuclear plants.

Material inventories that reflect evolving changes in plant design have not been adequately addressed in the open literature, however. It is therefore not feasible to address such design changes in the present analysis. Instead, the material inventories of individual facilities will be based on those of the reference facilities, adjusted only for the individual reactor's power rating.

##### A.5.2.1 Scaling Factors

It is reasonable to assume a correlation between a plant's power rating and its material inventory. By this means, data collected for Reference PWRs and BWRs can be utilized to estimate inventories for the industry at large. In reports prepared for the DOE, Argonne National Laboratory (ANL) employed a scaling method based on the mass of PWR and BWR pressure

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<sup>4</sup> A materials inventory for the stainless steel in the Reference BWR, such as the one for the PWR shown in Table A-30, could not be constructed from the available data.

vessels (Nuclear Engineering International 1991, 1992, 1993). ANL assumed that all metal inventories for both PWRs and BWRs can be calculated from those at the corresponding reference plant based on the design power, as follows:

$$M = M_r \left( \frac{P}{P_r} \right)^{\frac{2}{3}}$$

M = mass of metal (e.g., carbon steel) in actual reactor

M<sub>r</sub> = mass of same metal in reference reactor

P = power rating of actual reactor (MWe)

P<sub>r</sub> = power rating of reference reactor

The quantity,  $\left( \frac{P}{P_r} \right)^{\frac{2}{3}}$ , is referred to as the scaling factor.

#### A.5.2.2 U.S. Nuclear Power Industry

Table A1-1 in Appendix A-1 lists the 104 nuclear power reactors currently licensed to operate by the NRC. The table also lists the scaling factors for PWRs and BWRs in separate columns. Scaling was based on the net maximum dependable capacity reported by the NRC (U.S. NRC 2000). It is recognized that this capacity may vary with time and a more constant metric would be the licensed thermal capacity of each reactor. However, since the inventory of materials listed in Table A-29 is for a 1000 MWe PWR, scaling was based on electrical rather than thermal output. Given the other uncertainties inherent in the scaling process, this choice should not significantly affect inventory estimates.

In addition to the operating reactors, there are 27 nuclear power reactors which were formerly licensed to operate. (Of these, six were not light water reactors.) Only reactors which are in SAFSTOR or scheduled for DECON are included in this scrap metal analysis. Reactors where DECON is in progress or has been completed are excluded, as are reactors which are in an ENTOMB status. Thus, from the total population of formerly licensed nuclear power reactors, eight PWRs are included together with six BWRs and three other reactors (which are treated as BWRs<sup>5</sup>). Table A1-2 lists these 17 reactors, along with the scaling factors and dates when scrap metal releases might be expected.

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<sup>5</sup> These reactors include Fermi-1, CVTR and Peach Bottom-1. Since these are all small plants (less than 200 MWt), treating them as BWRs will have little impact on the total scrap metal inventories.

### A.5.2.3 Estimating the Metal Inventories of U.S. Nuclear Power Plants

The following relationship was used to estimate metal inventories of U.S. nuclear power plants:

$$M_i = m_{p_i} \sum_{j=1}^{77} s_{p_j} + m_{b_i} \sum_{j=1}^{44} s_{b_j} \quad (\text{A-1})$$

$M_i$  = total inventory of metal category  $i$  (e.g., contaminated stainless steel) from all nuclear power plants

$m_{p_i}$  = inventory of metal category  $i$  in Reference PWR

$s_{p_j}$  = scaling factor for actual PWR  $j$  (see Tables A1-1 and A1-2)

$m_{b_i}$  = inventory of metal category  $i$  in Reference BWR

$s_{b_j}$  = scaling factor for actual BWR  $j$  (see Tables A1-1 and A1-2)

The results are shown in Table A-81. Approximately 587,000 t of contaminated steel may, over time, become candidates for clearance. About 80% of the contaminated steel is carbon steel with stainless steel representing the balance. The terms “Total” and “Releasable” were explained in connection with Table A-80.

Table A-81. Steel Inventories of U.S. Nuclear Power Facilities (t)

	Reactor Type — Sum of Scaling Factors						Total Industry		
	PWR — 71.954			BWR — 34.249					
	All Steel	Carbon Steel	Stainless	All Steel	Carbon Steel	Stainless	All Steel	Carbon Steel	Stainless
Rebar		9.35e+05			6.16e+05			1.55e+06	
All Other		1.42e+06			5.48e+05			1.97e+06	
Total	2.50e+06	2.36e+06	1.50e+05	1.24e+06	1.16e+06	7.19e+04	3.74e+06	3.52e+06	2.22e+05
Releasable <sup>a</sup>	2.98e+05	2.38e+05	5.96e+04	2.89e+05	2.31e+05	5.78e+04	5.87e+05	4.69e+05	1.17e+05
Low <sup>b</sup>	7.56e+04	6.05e+04	1.51e+04	9.87e+04	7.90e+04	1.97e+04	1.74e+05	1.39e+05	3.49e+04
Medium <sup>c</sup>	4.12e+04	3.29e+04	8.23e+03	1.35e+05	1.08e+05	2.69e+04	1.76e+05	1.41e+05	3.52e+04
High <sup>d</sup>	1.81e+05	1.45e+05	3.62e+04	5.58e+04	4.46e+04	1.12e+04	2.37e+05	1.89e+05	4.73e+04

<sup>a</sup> Contaminated steel that can be potentially decontaminated to meet foreseeable clearance standards

<sup>b</sup> Low-level contamination:  $<10^5$  dpm/100 cm<sup>2</sup>

<sup>c</sup> Medium-level contamination:  $10^5$  —  $10^7$  dpm/100 cm<sup>2</sup>

<sup>d</sup> High-level contamination:  $>10^7$  dpm/100 cm<sup>2</sup>

The radioactive contaminants of most of the metal components that are candidates for clearance will be found on the surface. Therefore, in the preceding sections of this appendix, contamination levels have been cited as areal activity concentrations, in units of dpm/100 cm<sup>2</sup> or

Ci/m<sup>2</sup>. However, in the exposure scenarios discussed in Chapters 5 and 6, the radiation sources are modeled as bulk material. Thus, whether the source is a pile of assorted scrap, or the residually radioactive metal products and non-metallic byproducts of the steel refining process, contamination expressed as mass activity concentrations (i.e., specific activities), in units such as pCi/g, is a more meaningful quantity. Specific activities can be derived from areal activity concentrations by the following relationship:

$$S_{ij} = C_{ij} \sigma_j$$

$S_{ij}$  = specific activity of nuclide  $i$  in component  $j$  (pCi/g)

$C_{ij}$  = areal activity concentration of nuclide  $i$  in component  $j$  (pCi/cm<sup>2</sup> = 10<sup>8</sup> Ci/m<sup>2</sup>)

$\sigma_j$  = mass thickness of component  $j$  (g/cm<sup>2</sup>)

$$= \frac{m_j}{a_j}$$

$m_j$  = mass of component  $j$  (g)

$a_j$  = area of contaminated surface of component  $j$  (cm<sup>2</sup>)

Since the present radiological assessment addresses the clearance and subsequent recycle of large quantities of cleared metals rather than individual components, it is useful to calculate the average mass thickness of all carbon steel that will be potentially cleared from U.S. nuclear power facilities. This quantity can be expressed as follows:

$$\bar{\sigma}_c = \frac{A_p \sum_{j=1}^{77} s_{p_j} + A_b \sum_{j=1}^{44} s_{b_j}}{M_c}$$

$$A_p = \sum a_{p_i}$$

$a_{p_i}$  = area of component  $i$  of Reference PWR

$$A_b = \sum a_{b_i}$$

$a_{b_i}$  = area of component  $i$  of Reference BWR

$M_c$  = mass of all carbon steel potentially cleared from U.S. nuclear power facilities, given by Eq. A-1

The areas of the individual PWR components were based on data presented by Smith et al. (1978), while the corresponding BWR data was presented by Oak et al. (1980).

Table A-82. Average Mass Thickness of Carbon Steel Inventories

Reactor Type	Sum of Scaling Factors	Reference Reactor		Total Mass (g)	Total Area (cm <sup>2</sup> )
		Mass (g)	Area (cm <sup>2</sup> )		
PWR	71.954	3.31e+09	2.19e+08	2.38e+11	1.58e+10
BWR	34.249	6.75e+09	2.40e+09	2.31e+11	8.22e+10
Total				4.69e+11	9.80e+10
Mass Thickness (g/cm <sup>2</sup> )					4.79

A.5.3 Metal Inventories Other Than Steel

Although steel is clearly the predominant metal used in the construction and components of a nuclear power plant, there are also significant quantities of other metals. Tables A-29 lists the total inventories of nine metals for the Reference PWR. (In the absence of other data, the same total inventories were adopted for the Reference BWR.) There are no available data on the radiological contamination of these metals. However, most of these metals are in components that are made primarily of carbon steel. It is therefore assumed that these metals have contamination profiles similar to those of the carbon steel components of the Reference PWR and the Reference BWR, respectively.

Table A-83. Inventories of Metals Other Than Steel (t)

Metal	Total Inventory —Industry	Contaminated—Subject to Clearance*				
		Reference Facility		Nuclear Power Industry		
		PWR	BWR	All PWRs	All BWRs	Total
Galvanized Iron	138,064	131	258	9,460	8,844	18,304
Copper	73,280	70	137	5,021	4,694	9,715
Inconel	12,744	12	24	873	816	1690
Lead	4,885	4.7	9.1	335	313	648
Bronze	2,655	2.5	5.0	182	170	352
Aluminum	1,912	1.8	3.6	131	122	253
Brass	1,062	1.0	2.0	73	68	141
Nickel	106	0.1	0.2	7.3	6.8	14
Silver	<106	<0.1	<0.2	<7.0	<6.7	<14

\* Contaminated metals that can be potentially decontaminated to meet foreseeable clearance standards

#### A.5.4 Timetable for the Release of Scrap Metals from Nuclear Power Plants

The projected year of shutdown for each of 104 operating units is listed in Table A1-1. For the purpose of the present analysis, it was assumed that any scrap metal would be released ten years after reactor shutdown.<sup>6</sup> As described in Section A.5.2.2, Table A1-2 lists the 17 shut-down commercial nuclear power reactors included in the present analysis, along with the dates when significant scrap metal releases might be expected. Table A-84 summarizes the availability of scrap for each year during which one or more plants would begin releasing scrap metal. The amount of each metal released during that year is calculated by a formula similar to Eq. A-1:

$$M_{ik} = m_{p_i} \sum_{j=1}^{n_{kp}} s_{p_j} + m_{b_i} \sum_{j=1}^{n_{kb}} s_{b_j}$$

$M_{ik}$  = total inventory of metal  $i$  from all nuclear plants dismantled in year  $k$

$n_{kp}$  = number of PWRs dismantled in year  $k$

$n_{kb}$  = number of BWRs dismantled in year  $k$

Columns 2 and 3 list the sum of the scaling factors of the PWR and BWR plants, respectively, that are expected to begin major decommissioning activities in the year listed in Column 1. The remaining columns list the mass of each metal that would be released that year, assuming that all metal from a given plant would be released in one year. It is recognized that, in fact, the releases from each plant would span a period of several years, and that there would be considerable overlap in the releases from various plants that shut down within a few years of each other. Nevertheless, this table presents an overview of the anticipated rate of release in future years. The actual release dates of scrap metal may be later than those listed. First, as mentioned in Note 1, a number of reactors may receive 20-year extensions to their operating licenses, thereby delaying the projected date of decommissioning. Some facilities are likely to elect the SAFSTOR decommissioning alternative, thereby delaying releases for up to 50 years.

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<sup>6</sup> In the case of reactors for which the SAFSTOR decommissioning alternative was selected, clearance is assumed to occur 60 years after shutdown (see Appendix A-1).

Table A-84. Anticipated Releases of Scrap Metals from Nuclear Power Plants (t)

Year	Σ scaling factors <sup>a</sup>		Carbon Steel	Stainless Steel	Galvanized Iron	Copper	Inconel	Lead	Bronze	Aluminum	Brass	Nickel
	PWR	BWR										
2006	1.48	0	4,906	1,227	195	103	18	6.9	3.7	2.7	1.5	0.15
2007	0	0.17	1,169	292	45	24	4	1.6	0.86	0.62	0.34	0.034
2016	0	0.84	5,683	1,421	217	115	20	7.7	4.2	3.0	1.7	0.17
2019	0.6	1.41	11,522	2,881	444	235	41	16	8.5	6.1	3.4	0.34
2020	1.39	0.67	9,111	2,278	355	189	33	13	6.8	4.9	2.7	0.27
2021	0.81	0.84	8,372	2,093	324	172	30	11	6.2	4.5	2.5	0.25
2022	1.65	3.08	26,266	6,568	1,012	537	93	36	19	14	7.8	0.78
2023	5.12	2.16	31,573	7,894	1,232	654	114	44	24	17	9.5	0.95
2024	3.38	6.11	52,479	13,122	2,023	1,074	187	72	39	28	16	1.6
2025	1.89	0	6,252	1,563	248	132	23	8.8	4.8	3.4	1.9	0.19
2026	3.71	1.88	24,978	6,245	973	517	90	34	19	13	7.5	0.75
2027	2.82	0.1	9,844	2,461	390	207	36	14	7.5	5.4	3.0	0.30
2028	1.83	0.87	11,922	2,981	465	247	43	16	8.9	6.4	3.6	0.36
2030	3.08	0	10,202	2,551	405	215	37	14	7.8	5.6	3.1	0.31
2031	4.09	0	13,527	3,382	537	285	50	19	10	7.4	4.1	0.41
2032	3.06	3.35	32,775	8,195	1,268	673	117	45	24	18	9.8	0.98
2033	1.97	2.09	20,675	5,170	800	425	74	28	15	11	6.2	0.62
2034	5.8	2.24	34,307	8,578	1,340	711	124	47	26	19	10	1.0
2035	4.4	1.87	27,206	6,802	1,062	564	98	38	20	15	8.2	0.82
2036	5.23	4.3	46,335	11,585	1,797	954	166	64	35	25	14	1.4
2037	5.36	0	17,730	4,433	704	374	65	25	14	9.8	5.4	0.54
2038	1.16	0.35	6,229	1,558	244	129	23	8.6	4.7	3.4	1.9	0.19
2039	1.99	1.08	13,847	3,462	539	286	50	19	10	7.5	4.1	0.41
2040	1.1	0	3,634	909	144	77	13	5.1	2.8	2.0	1.1	0.11
2043	2.89	0	9,556	2,389	380	201	35	13	7.3	5.3	2.9	0.29
2044	1.78	0	5,896	1,474	234	124	22	8.3	4.5	3.2	1.8	0.18
2045	1.08	0	3,564	891	142	75	13	5.0	2.7	2.0	1.1	0.11
2046	0.89	0	2,947	737	117	62	11	4.1	2.3	1.6	0.90	0.090
2047	0	0.14	917	229	35	19	3.2	1.2	0.67	0.49	0.27	0.027
2049	0.88	0	2,928	732	116	62	11	4.1	2.2	1.6	0.89	0.089
2052	0.55	0	1,809	452	72	38	6.6	2.5	1.4	0.99	0.55	0.055
2056	0.98	0	3,255	814	129	69	12	4.6	2.5	1.8	0.99	0.10
2057	0.98	0	3,255	814	129	69	12	4.6	2.5	1.8	1.0	0.10
2058	0	0.71	4,820	1,205	184	98	17	6.5	3.5	2.6	1.4	0.14
Total	72	34.2	469,490	117,389	18,304	9,715	1,690	648	352	253	141	14

<sup>a</sup> Values displayed are rounded; however, full precision was used in calculation

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**APPENDIX A-1**

**U.S. COMMERCIAL NUCLEAR POWER REACTORS**

## **U.S. COMMERCIAL NUCLEAR POWER REACTORS**

Table A1-1 presents a list of the 104 commercial nuclear power reactors in the U.S. currently licensed to operate by the NRC. The reactor type (BWR or PWR) is listed, along with its electrical generating capacity, and its scaling factor, which is described in Section A.5.2.1. The scaling factors for PWRs and BWRs are listed in separate columns to enable the sum of these factors for each type of reactor to be calculated separately; however, the factors for individual PWRs and BWRs are calculated by the same formula. The year of projected shutdown is based on the expiration date of the current operating license, including, in three cases, credit for construction recapture. Construction recapture is defined as “[t]he maximum number of years that could be added to the license expiration date to recover the period from the construction permit to the date when the operating license was granted. A licensee is required to submit an application for such a change.” (U.S. NRC 2000)

Table A1-1. Nuclear Power Reactors Currently Licensed to Operate

Electric Utility	Reactor	Type	Power Rating (MWe) <sup>a</sup>	Scaling Factor <sup>b</sup>		Year of Projected Shutdown
				PWR	BWR	
Arizona Public Service	Palo Verde 1	PWR	1,227	1.146	—	2024
Arizona Public Service	Palo Verde 2	PWR	1,227	1.146	—	2025
Arizona Public Service	Palo Verde 3	PWR	1,230	1.148	—	2027
Baltimore Gas & Electric	Calvert Cliffs 1	PWR	835	0.887	—	2034
Baltimore Gas & Electric	Calvert Cliffs 2	PWR	840	0.890	—	2036
Boston Edison	Pilgrim 1	BWR	670	—	0.766	2012
Carolina Power & Light	Brunswick 1	BWR	767	—	0.838	2016
Carolina Power & Light	Brunswick 2	BWR	754	—	0.828	2014
Carolina Power & Light	H. B. Robinson 2	PWR	683	0.776	—	2010
Carolina Power & Light	Shearon Harris 1	PWR	860	0.904	—	2026
Centerior Energy	Davis-Besse	PWR	873	0.913	—	2017
Cleveland Electric	Perry 1	BWR	1,160	—	1.104	2026
Commonwealth Edison	Braidwood 1	PWR	1,100	1.066	—	2026
Commonwealth Edison	Braidwood 2	PWR	1,100	1.066	—	2027
Commonwealth Edison	Byron 1	PWR	1,105	1.069	—	2024
Commonwealth Edison	Byron 2	PWR	1,105	1.069	—	2026
Commonwealth Edison	Dresden 2	BWR	772	—	0.842	2006
Commonwealth Edison	Dresden 3	BWR	773	—	0.842	2011
Commonwealth Edison	LaSalle 1	BWR	1,036	—	1.024	2022
Commonwealth Edison	LaSalle 2	BWR	1,036	—	1.024	2023
Commonwealth Edison	Quad Cities 1	BWR	769	—	0.839	2012
Commonwealth Edison	Quad Cities 2	BWR	769	—	0.839	2012
Consolidated Edison	Indian Point 2	PWR	951	0.967	—	2013
Consumers Energy	Palisades 1	PWR	730	0.811	—	2011 <sup>c</sup>
Detroit Edison	Fermi 2	BWR	876	—	0.916	2025
Duke Power	Catawba 1	PWR	1,129	1.084	—	2024
Duke Power	Catawba 2	PWR	1,129	1.084	—	2026
Duke Power	McGuire 1	PWR	1,129	1.084	—	2021
Duke Power	McGuire 2	PWR	1,129	1.084	—	2023
Duke Power	Oconee 1	PWR	846	0.895	—	2033
Duke Power	Oconee 2	PWR	846	0.895	—	2033
Duke Power	Oconee 3	PWR	846	0.895	—	2034
Duquesne Light	Beaver Valley 1	PWR	810	0.869	—	2016
Duquesne Light	Beaver Valley 2	PWR	820	0.876	—	2027
Entergy Operations, Inc.	Arkansas Nuclear 1	PWR	836	0.887	—	2014
Entergy Operations, Inc.	Arkansas Nuclear 2	PWR	858	0.903	—	2018
Entergy Operations, Inc.	Grand Gulf 1	BWR	1,179	—	1.116	2022

Source: U.S. NRC 2000

<sup>a</sup> Net maximum dependable capacity

<sup>b</sup> Scaling factor = (power rating/1000)<sup>2/3</sup> (see text)

<sup>c</sup> Year assuming construction recapture

Table A1-1 (continued)

Electric Utility	Reactor	Type	Power Rating (MWe) <sup>a</sup>	Scaling Factor <sup>b</sup>		Year of Projected Shutdown
				PWR	BWR	
Entergy Operations, Inc.	River Bend 1	BWR	936	—	0.957	2025
Entergy Operations, Inc.	Waterford 3	PWR	1,104	1.068	—	2024
Florida Power Corp.	Crystal River 3	PWR	818	0.875	—	2016
Florida Power & Light	St. Lucie 1	PWR	839	0.890	—	2016
Florida Power & Light	St. Lucie 2	PWR	839	0.890	—	2023
Florida Power & Light	Turkey Point 3	PWR	693	0.783	—	2012
Florida Power & Light	Turkey Point 4	PWR	693	0.783	—	2013
GPU Nuclear	Oyster Creek	BWR	619	—	0.726	2009
GPU Nuclear	Three Mile Island 1	PWR	786	0.852	—	2014
Illinois Power	Clinton	BWR	930	—	0.953	2026
Indiana/Michigan Power	D. C. Cook 1	PWR	1,000	1.000	—	2014
Indiana/Michigan Power	D. C. Cook 2	PWR	1,060	1.040	—	2017
IES Utilities	Duane Arnold	BWR	520	—	0.647	2014
Nebraska Public Power	Cooper	BWR	764	—	0.836	2014
New York Power Authority	James A. Fitzpatrick	BWR	762	—	0.834	2014
New York Power Authority	Indian Point 3	PWR	965	0.977	—	2015
Niagara Mohawk	Nine Mile Point 1	BWR	565	—	0.683	2009
Niagara Mohawk	Nine Mile Point 2	BWR	1,105	—	1.069	2026
North Atlantic Energy	Seabrook 1	PWR	1,158	1.103	—	2026
Northeast Nuclear Energy	Millstone 2	PWR	871	0.912	—	2015
Northeast Nuclear Energy	Millstone 3	PWR	1,137	1.089	—	2025
Northern States Power	Monticello	BWR	544	—	0.666	2010
Northern States Power	Prairie Island 1	PWR	513	0.641	—	2013
Northern States Power	Prairie Island 2	PWR	512	0.640	—	2014
Omaha Public Power	Fort Calhoun	PWR	478	0.611	—	2013
Pacific Gas & Electric	Diablo Canyon 1	PWR	1,073	1.048	—	2021
Pacific Gas & Electric	Diablo Canyon 2	PWR	1,087	1.057	—	2025
PECO Energy	Peach Bottom 2	BWR	1,093	—	1.061	2013
PECO Energy	Peach Bottom 3	BWR	1,093	—	1.061	2014
Pennsylvania Power	Susquehanna 1	BWR	1,090	—	1.059	2022
Pennsylvania Power	Susquehanna 2	BWR	1,094	—	1.062	2024
Philadelphia Electric	Limerick 1	BWR	1,105	—	1.069	2024
Philadelphia Electric	Limerick 2	BWR	1,115	—	1.075	2029
Public Service E & G	Hope Creek 1	BWR	1,031	—	1.021	2026
Public Service E & G	Salem 1	PWR	1,115	1.075	—	2016
Public Service E & G	Salem 2	PWR	1,115	1.075	—	2020
Rochester Gas & Electric	Ginna 3	PWR	470	0.605	—	2009
South Carolina E & G	Summer	PWR	945	0.963	—	2022

<sup>a</sup> Net maximum dependable capacity

<sup>b</sup> Scaling factor = (power rating/1000)<sup>2/3</sup> (see text)

Table A1-1 (continued)

Electric Utility	Reactor	Type	Power Rating (MWe) <sup>a</sup>	Scaling Factor <sup>b</sup>		Year of Projected Shutdown
				PWR	BWR	
Southern California Edison	San Onofre 2	PWR	1,070	1.046	—	2022 <sup>c</sup>
Southern California Edison	San Onofre 3	PWR	1,080	1.053	—	2022 <sup>c</sup>
Southern Nuclear	Edwin I. Hatch 1	BWR	805	—	0.865	2014
Southern Nuclear	Edwin I. Hatch 2	BWR	809	—	0.868	2018
Southern Nuclear	Joseph M. Farley 1	PWR	812	0.870	—	2017
Southern Nuclear	Joseph M. Farley 2	PWR	822	0.878	—	2021
Southern Nuclear	Vogtle 1	PWR	1,162	1.105	—	2027
Southern Nuclear	Vogtle 2	PWR	1,162	1.105	—	2029
STP Nuclear	South Texas 1	PWR	1,251	1.161	—	2027
STP Nuclear	South Texas 2	PWR	1,251	1.161	—	2028
Tennessee Valley Authority	Browns Ferry 1	BWR	1,065 <sup>d</sup>	—	1.043	2013
Tennessee Valley Authority	Browns Ferry 2	BWR	1,065	—	1.043	2014
Tennessee Valley Authority	Browns Ferry 3	BWR	1,065	—	1.043	2016
Tennessee Valley Authority	Sequoia 1	PWR	1,117	1.077	—	2020
Tennessee Valley Authority	Sequoia 2	PWR	1,117	1.077	—	2021
Tennessee Valley Authority	Watts Bar 1	PWR	1,117	1.077	—	2035
Texas Utilities Electric	Comanche Peak 1	PWR	1,150	1.098	—	2030
Texas Utilities Electric	Comanche Peak 2	PWR	1,150	1.098	—	2033
Union Electric	Callaway	PWR	1,171	1.111	—	2024
Vermont Yankee Nuclear	Vermont Yankee	BWR	510	—	0.638	2012
Virginia Electric & Power	North Anna 1	PWR	893	0.927	—	2018
Virginia Electric & Power	North Anna 2	PWR	897	0.930	—	2020
Virginia Electric & Power	Surry 1	PWR	801	0.862	—	2012
Virginia Electric & Power	Surry 2	PWR	801	0.862	—	2013
Washington Public Power	Washington Nuclear 2	BWR	1,107	—	1.070	2023
Wisconsin Electric Power	Point Beach 1	PWR	485	0.617	—	2010
Wisconsin Electric Power	Point Beach 2	PWR	485	0.617	—	2013
Wisconsin Public Service	Kewaunee	PWR	511	0.639	—	2013
Wolf Creek Nuclear	Wolf Creek 1	PWR	1,163	1.106	—	2025
Total				65.866	32.327	

<sup>a</sup> Net maximum dependable capacity

<sup>b</sup> Scaling factor = (power rating/1000)<sup>2/3</sup> (see text)

<sup>c</sup> Assuming construction recapture

<sup>d</sup> Based on design characteristics—reactor has no fuel loaded and requires NRC approval to restart.

Table A1-2 lists the commercial nuclear power reactors that were formerly licensed but have been shut down. As was stated in Section A.5.2.2, the list excludes reactors whose owners have chosen the ENTOMB decommissioning alternative, and those with the DECON alternative that have begun or already completed decommissioning. It is unlikely that reactors in these categories would be clearing scrap metal in the foreseeable future. As before, scaling factors for PWR and BWR plants are listed in separate columns. For the purpose of the present analysis, the three non-light water reactors are treated as if they were BWRs.

The last column lists the date that significant quantities of scrap metal would be released from these reactors. For reactors in SAFSTOR, this is assumed to be 60 years after the shutdown date, while for those with the DECON alternative it is ten years after shutdown.

Table A1-2. Formerly Licensed Nuclear Power Reactors

Reactor	Type	Power Rating (MWe) <sup>a</sup>	Scaling Factor <sup>b</sup>		Alternative <sup>c</sup>	Year	
			PWR	BWR		Shutdown	Release <sup>d</sup>
Big Rock Point	BWR	72	—	0.173	DECON	1997	2007
CVTR	PTHW <sup>e</sup>	20	—	0.074	SAFSTOR	1967	2027
Dresden 1	BWR	210	—	0.353	SAFSTOR	1978	2038
Fermi 1	SCF <sup>e</sup>	60	—	0.153	SAFSTOR	1972	2032
GE VBWR	BWR	15	—	0.061	SAFSTOR	1963	2023
Haddam Neck	PWR	548	0.670	—	DECON	1996	2006
Humboldt Bay	BWR	60	—	0.153	SAFSTOR	1976	2036
Indian Point 1	PWR	185	0.325	—	SAFSTOR	1974	2034
La Crosse	BWR	50	—	0.136	SAFSTOR	1987	2047
Maine Yankee	PWR	732	0.812	—	DECON	1996	2006
Millstone 1	BWR	603	—	0.714	SAFSTOR	1998	2058
Peach Bottom 1	HTGR <sup>e</sup>	34	—	0.105	SAFSTOR	1974	2034
Rancho Seco	PWR	832	0.885	—	SAFSTOR <sup>f</sup>	1989	2049
San Onofre 1	PWR	404	0.547	—	SAFSTOR	1992	2052
Three Mile Island 2	PWR	831	0.884	—	<sup>g</sup>	1979	2039
Zion 1	PWR	975	0.983	—	SAFSTOR	1997	2057
Zion 2	PWR	975	0.983	—	SAFSTOR	1996	2056
Total	shut down reactors (see note)		6.088	1.922			
	including currently licensed reactors		71.954	34.249			

Source: U.S. NRC 2000

Note: excludes reactors at which DECON has started or been completed and those in ENTOMB status

<sup>a</sup> Licensed thermal capacity × 0.3

<sup>b</sup> Scaling factor = (power rating/1000)<sup>2/3</sup> (see text)

<sup>c</sup> Selected decommissioning alternative

<sup>d</sup> Year that significant quantities of scrap metal will be released—10 years after shutdown for the DECON alternative, 60 years for SAFSTOR

<sup>e</sup> Metals inventory and contamination levels assumed same as for BWR

<sup>f</sup> Dismantlement of radioactive secondary piping and components is ongoing

<sup>g</sup> In monitored storage until TMI-1 is shut down, then both will be decommissioned

## REFERENCE

U.S. Nuclear Regulatory Commission (U.S. NRC). 2000. "Information Digest, 2000 Edition," NUREG-1350, Volume 12. U.S. NRC, Washington, DC.

**APPENDIX B**

**ALUMINUM RECYCLING**

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## ALUMINUM RECYCLING

This appendix provides information on the recycling of aluminum and the use of its products, byproducts, and wastes.

### B.1 INVENTORY

Based on the review provided in this section, the total quantity of aluminum scrap metal, both clean and potentially contaminated, attributable to the nuclear industry, is listed in Table B-1.

Table B-1. Aluminum Scrap Potentially Available from Nuclear Facilities (t)

Commercial Nuclear Power Plants		DOE Facilities	Total
Total	Contaminated	Contaminated	Contaminated
1,900	253	36,070	36,323

A more recent DOE summary states that the total aluminum available as radioactive scrap metal from DOE and NRC-licensed facilities (other than nuclear power plants) is 30,000 tons<sup>1</sup> (Adams 1998). Presumably this is contaminated and suspect contaminated material. The DOE estimate is in reasonable agreement with the quantities tabulated above.

#### B.1.1 Scrap Metal Inventory

Chapter 4 of the present report summarizes information on the potential quantities of aluminum scrap available for recycle from DOE and commercial facilities. However, there is no available information as to the portion of the aluminum that may be contaminated and the radionuclide composition of the contamination. Most of the aluminum from commercial nuclear power plants is expected to be in gratings, switch gear, and component housings. It is proposed in Section 4.2.2 that, for the purpose of the present analysis, a reasonable approach is to assume that the contaminated fraction of aluminum among total nuclear power plant scrap metal inventories

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<sup>1</sup> This appendix includes numerous references with widely varying units of measurement. The authors of this appendix have generally chosen not to convert the units to a consistent system but rather have chosen to quote information from the various sources in the original units. When the cited information is distilled into scenarios for modeling doses and risks, consistent units are used.

parallels the contaminated fraction of carbon steel for the Reference BWR and the Reference PWR.

According to Table A-83, the total of amount of aluminum in all commercial nuclear power reactors is about 1,900 metric tons (t). Only a fraction of this inventory is expected to be significantly contaminated and not all of the contaminated inventory may be potentially suitable for recycling. Assuming that all metals have the same contamination profiles as steel, it is estimated that 20% of the aluminum in the Reference BWR and 10% in the Reference PWR is contaminated but potentially recyclable<sup>2</sup>. Applying these factors to the entire U.S. commercial nuclear power industry yields 122 t from all BWRs and 131 t from all PWRs, for a total of 253 t.

For currently operating reactors, it is assumed that the scrap will be available ten years after the expiration of the current operating license. The methodology for assessing formerly licensed reactors is presented in Appendix A-1. Using this decommissioning schedule, annual availability of scrap can be established as shown in Table B-2 (based on Appendix A, Table A-84). It can be seen that 28 t of aluminum would be released from commercial nuclear power plants in the peak year: 2024.

Based on a survey of DOE data, it is estimated that 2,353 t of contaminated, potentially releasable aluminum were in inventory at the end of 1996 (see Table 4-4) and that 33,717 t of contaminated aluminum will be generated from future decommissioning activities, resulting in a total of 36,070 t of contaminated aluminum (see Table 4-5)<sup>3</sup>. Approximately 98% of this aluminum scrap is expected to come from dismantling the gaseous diffusion plants (GDP) at K-25 (Oak Ridge, Tenn.), Portsmouth, Ohio, and Paducah, Ky. Decommissioning schedules for the diffusion plants are assumed to be as follows (see Section 4.1.5):

- K-25 ..... 1998 to 2006
- Portsmouth ..... 2007 to 2015

---

<sup>2</sup> Garbay and Chapuis (1991) concluded that a PWR contained 20 to 100 t of aluminum, mostly as electrical cable. The authors assumed that about 25% was contaminated and selected 20 t as the value for modeling exposures. They further assumed that two PWRs would be decommissioned each year, resulting in 40 t of contaminated aluminum available for recycle annually.

<sup>3</sup> This value appears to be conservative (i.e., high) since Compere et al. (1996) note that only 20,100 t of radioactive aluminum/copper will be available from the three diffusion plants while Table 4-5 lists a total of 35,300 t.

- Paducah ..... 2015 to 2023

For the purposes of analyzing the DOE facilities, it was assumed that no scrap metal is generated in the first year (of a nine-year decommissioning period), 9% is generated in the final year, and 13% is generated in each of years 2 through 8.

Table B-2. Availability of Potentially Contaminated Aluminum from Nuclear Facilities (t)

Year	DOE Facilities	Commercial Nuclear Power Plants	Year	Commercial Nuclear Power Plants
2003	7237	—	2027	5.4
2004	979	—	2028	6.4
2005	979	—	2030	5.6
2006	679	2.7	2031	7.4
2007	—	0.6	2032	18
2008	780	—	2033	11
2009	780	—	2034	19
2010	780	—	2035	15
2011	780	—	2036	25
2012	780	—	2037	9.8
2013	780	—	2038	3.4
2014	780	—	2039	7.5
2015	540	—	2040	2.0
2016	2,636	3.0	2043	5.3
2017	2,636	—	2044	3.2
2018	2,636	—	2045	2.0
2019	2,636	6.1	2046	1.6
2020	2,636	4.9	2047	0.5
2021	2,636	4.5	2049	1.6
2022	2,636	14	2052	1.0
2023	1,746	17	2056	1.8
2024	—	28	2057	1.8
2025	—	3.4	2058	2.6
2026	—	13		
Total	36,075			253

Note: Values may differ to roundoff error

Although dismantlement of the K-25 facilities is in progress, DOE is not currently releasing any scrap metals generated in the process. In January 2000, the Secretary of Energy issued a moratorium on the Department’s release of volumetrically contaminated metals “pending a decision by the ... NRC... whether to establish national standards.... On July 13, 2000, the Secretary of Energy issued a memorandum ... [which] suspended the unrestricted release for recycling of scrap metal from radiological areas within DOE facilities. This suspension will remain in effect until improvements in DOE release criteria and information management have been developed and implemented” (Michaels 2000). Based on these DOE policy decisions, it is assumed in this report that releases of scrap metal from DOE facilities will not begin until 2003.

Some information as to the breakdown by location of aluminum scrap in the DOE inventory can be found in U.S. DOE 1996, vol. 2. These data are reproduced in Table B-3. Since most of this material is not specified to be clean or contaminated in the source document, the same methodology used in Chapter 4 is applied here. Table 4-4 indicates that 27 t are “clean,” 14 t contaminated, and 5,637 t “unspecified.” It was therefore assumed that 34.1% ( $14 \div [14 + 27] = 0.341$ ) of the “unspecified material” at each site was contaminated while the rest was clean. Furthermore, the quantity reported for each site was multiplied by a scaling factor of 1.213 to ensure that the total of all the sites conform to the totals in Table 4-4.

Table B-3. Current Inventory of Potentially Contaminated Aluminum Scrap at DOE Facilities (t)

Site	Clean	Contaminated	Unspecified	Total	Contaminated		
					Assumed	Total	Scaled <sup>a</sup>
K-25	—	—	1,100	1,100	376	376	456
ORNL	—	—	20	20	7	7	8
Y-12	—	—	38	38	13	13	16
Paducah	—	—	4,165	4,165	1,422	1,422	1,725
Portsmouth	—	—	314	314	107	107	130
Total	27	14	5,637	5,678	1,925	1,939	2,352

Source: U.S. DOE 1996, vol. 2, Appendix A6, Table 2-1

Note: Values may differ to roundoff error

The contaminated aluminum scrap from future decommissioning activities at facilities other than the diffusion plants—766 t—is assumed to be released uniformly over the period 2016 to 2022.

The availability of potentially recyclable aluminum scrap from DOE facilities is summarized in Table B-2. Clearly, any aluminum scrap recycling scenarios will be dominated by scrap from DOE facilities rather than from nuclear power plants. The maximum amount of scrap available in any year is 7237 t, which is the expected inventory by the year 2003. The largest source of this material is the K-25 plant.

### B.1.2 Radionuclide Inventory

As noted above, about 98% of the aluminum scrap from the DOE complex will be generated from the decommissioning of the gaseous diffusion plants at Portsmouth, Paducah, and Oak Ridge. The radioactive contamination of these materials is attributed to a limited suite of radionuclides. The predominant contaminants are isotopes of uranium and their radioactive progenies. Smaller amounts of Tc-99 and trace quantities of Pu-239 and Np-237 may also be present. Indicated contamination levels for aluminum scrap metal items in inventory at the diffusion plants are as follows (U.S. DOE 1986):

- U/U-235 ..... <500 ppm
- Tc-99 ..... <10 ppm
- Np-237 ..... <0.05 ppb
- Pu-239 ..... <0.05 ppb
- Th ..... <500 ppm

It has been estimated that the following radionuclide inventories were fed to the Paducah GDP (National Research Council 1996, Appendix E):

- U-236 ..... 900 Ci
- Tc-99 ..... 11,200 Ci
- Np-237 ..... 13 Ci
- Pu-239 ..... 20 Ci
- Th-230+D ..... 140 Ci
- Pa-231+D ..... 16 Ci

Much of this activity was removed during the cascade upgrade and improvement programs.

Recent studies have shown that, for the cast aluminum compressor blades used in the diffusion plants, much of the contamination is internal, caused by  $UF_6$  entering surface-connected voids (Compere et al. 1996). The  $UF_6$  hydrolyzes to  $UO_2F_2$  (National Research Council 1996).

## B.2 RECYCLING OF ALUMINUM SCRAP

### B.2.1 Secondary Aluminum

Secondary aluminum, or the aluminum recovered from scrap, has become an important component of the supply/demand relationship in the United States. The industry's recycling operations, commonly referred to as the "secondary aluminum industry," use purchased scrap as "raw" material. Purchased aluminum scrap is classified as "new" (manufacturing) scrap and "old" scrap (discarded aluminum products).

In 1996, metal recovered from both new and old scrap reached a historic high of approximately 3.3 million tons, according to data derived by the U.S. Geological Survey from its "Aluminum Scrap" survey of 90 U.S. companies and/or plants (Plunkert 1997a). Fifty-three percent of this recovered metal came from new scrap and 47% from old scrap. The predominant type of purchased scrap was aluminum used beverage container (UBC) scrap, accounting for more than one-half of the old scrap consumed.

Aluminum recovered from scrap has increased tenfold since 1950. The recovery of aluminum from old scrap has shown an even more rapid expansion over the same period of time. Increased costs for energy and growing concerns over waste management have provided the impetus for increased recycling rates. Improvements in recycling technologies and changes in the end-use consumption patterns have also contributed to the increase in aluminum scrap recovery.

### B.2.2 Composition of Scrap Aluminum

Aluminum scrap enters the supply stream of the secondary aluminum industry through two major, broadly classified sources: (1) new scrap, generated by the fabrication of aluminum products, and (2) old scrap, which becomes available when consumer products have reached the end of their economic life and have been discarded. New scrap includes solids, such as new casting scrap, clippings or cuttings of new sheet, rod, wire and cable, borings and turnings from

machining operations; residues (e.g. drosses, skimmings, spillings, and sweepings); and surplus products (mill products and castings). Old scrap includes products such as automobiles, aluminum windows/doors/siding, used beverage cans, and cooking utensils. Obsolete industrial products, such as transmission cables, aircraft, and other similar items; outdated inventory materials; production overruns; out-of-specification products; etc., are also classified as old scrap.

Aluminum alloys are divided into two distinct categories according to how they are formed: cast alloys and wrought alloys. Controlling the composition of aluminum recovered from scrap is essential to producing marketable secondary alloys. Cast alloys are those specially formulated to flow into a sand or permanent mold, to be die cast, or to be cast by any other process into the final form for end use. Wrought alloys are alloys that have been mechanically worked after casting. The “wrought” category is broad, since aluminum can be formed by virtually every known process. Wrought forms include sheet and plate, foil, extrusions, bar and rod, wire, forgings, and tubing.

The application or end product use of the aluminum determines which of these two major alloy categories is employed for the product. Application requirements determine the specific alloying elements and proportions of each element present in the product.

The mix of alloys recovered in aluminum scrap at a given time varies depending on (1) patterns of use and discard of these products, (2) the collection systems that act to intercept the discarded waste materials, (3) the separation efficiency with regard to control of scrap shape and size, and (4) degree of processing required to remove certain contaminants.

New industrial scrap, assuming proper segregation and identification, can be melted with minimal corrective additions. The processing of post consumer scrap, on the other hand, is much more difficult to predict because the scrap has a variable composition.

### B.3 STRUCTURE OF THE SCRAP INDUSTRY

Aluminum scrap is handled by both major segments of the aluminum industry: (1) the primary producers (integrated aluminum companies), and (2) independent secondary producers. The primary producers recover aluminum from bauxite ore via an electrolytic process in cells or “pots.” Such large pot-line plants are devoted to the production of ingots alloyed to particular

specifications necessary for fabrication of various products. The primary aluminum production plants do not recycle any outside material; however, an integrated aluminum company will utilize scrap aluminum feed in other facilities, separate from the primary pot-line plant.

In general, the primary producers practice recycle, mostly for UBC's, in large reverberatory smelters. They also recycle "new" scrap from their customers in very large smelters, and return the particular product to their customers. Such plants are not suitable for a feed scrap stream having many different alloy compositions since, if the smelter produced an "off-spec" material, the rework of very large smelter volumes makes such an event very costly. Primary producers consumed 2,180,000 t of old and new scrap in 1995, as summarized in Table B-4.

Table B-4. U.S. Consumption of Aluminum Scrap by Primary Producers, Foundries, Independent Mill Fabricators and Others in 1995 (t)

NEW SCRAP	
Solids	783,000
Borings and turnings	31,600
Dross and skimmings	15,900
Other <sup>a</sup>	198,000
Total New Scrap	1,028,500
OLD SCRAP	
Castings, sheet, clippings	329,000
Aluminum-copper radiators	2,710
Aluminum cans	799,000
Other <sup>b</sup>	14,200
Total Old Scrap	1,144,910
Sweated Pig	10,300
Grand Total	2,183,710

<sup>a</sup> Includes foil, can stock clippings and other miscellaneous.

<sup>b</sup> Includes municipal waste and fragmented auto shredder scrap.

In 1996, about 15.5% of all scrap processed by the primary and secondary smelters (567,000 t) was handled under tolling arrangements where the smelter remelts the scrap and returns it to the supplier (Plunkert 1997a).

A great variety of feed compositions are now handled by the independent secondary producers and it can be expected that recycle of decontaminated material, being diverse in alloy composition, will go to these producers, with their smaller smelters and experience with varying feeds.

#### B.4 SECONDARY ALUMINUM INDUSTRY

The secondary aluminum industry comprises those firms which melt aluminum scrap and manufacture various mill products which are sold to foundries and fabricators. In 1995, secondary aluminum smelters consumed 1,300,000 t of purchased new and old aluminum scrap and recovered 1,050,000 t of metal containing 978,000 t of aluminum (Plunkert 1996). The sources of this scrap are summarized in Table B-5.

Table B-5  
U.S. Consumption of Purchased Old and New Scrap by Secondary Smelters in 1995 (t).

NEW SCRAP	
Solids	177,000
Borings and Turnings	204,000
Dross and Skimmings	208,000
Other <sup>a</sup>	207,000
Total New Scrap	796,000
OLD SCRAP	
Castings, Sheet, Clippings	324,000
Aluminum-Copper Radiators	10,200
Aluminum Cans <sup>b</sup>	118,000
Other <sup>c</sup>	44,500
Total Old Scrap	496,700
Sweated Pig	4,340
Total Secondary Smelters	1,297,040

<sup>a</sup> Includes data on foil, can stock clippings, and other miscellaneous.

<sup>b</sup> Includes UBCs toll treated for primary producers

<sup>c</sup> Includes municipal waste (includes litter) and fragmented scrap (auto shredder)

According to a recent EPA report, the secondary aluminum industry operates about 68 plants<sup>4</sup> and employs about 3,600 (U.S. EPA 1995). Another source states that the North American industry involves 46 companies with 81 smelting operations (Novelli 1997). A major product of the secondary smelters is feed stock for production of aluminum castings. Aluminum casting alloys are tolerant to a variety of alloying elements, so mixed scrap can be used. If the scrap is carefully segregated, wrought alloys with less tolerance to impurities can be produced. It is this segment of the industry which is of primary interest to the present analysis, since it is the segment which processes a wide variety of scrap materials and typically utilizes nearly 100% scrap in the recycle operation. In practice, secondary smelter sourcing, processing, and marketing can be highly complex. Illustrative of this are the operations at IMCO Recycling Inc.—a publicly-owned company broadly involved in aluminum recycling. In 1996, IMCO had available 1,575 million pounds of aluminum recycling capacity at nine facilities and experienced a 92% operating rate. Scrap materials recycled included dross, used beverage cans, post-consumer and commercial scrap, and new scrap from manufacture of cans and other products. About one-half of the material was from the beverage can and packaging industry; the balance was from transportation and construction market sectors. The product mix was 40% for cans and packaging, 27% for construction and 23% for transportation. The balance was supplied to the steel industry and miscellaneous customers. In 1997, IMCO expected that 90% of production would involve tolling arrangements for customer-owned materials while the remainder would be based on buy/sell transaction which involve purchase of scrap aluminum on the open market, and then processing and selling it (IMCO 1997).

In contrast, Wabash Alloys, which has five U.S. smelters and one in Canada, purchases all of its scrap from the open market and mainly produces casting alloys which are sold to the automotive industry (Viland 1990). A flow diagram for typical secondary smelter processing is shown in Figure B-1.

#### B.4.1 Scrap Handling and Preparation

Scrap is purchased for a given facility from hundreds of brokers and dealers. In contrast to carbon steel, shipping costs are not a major factor in the aluminum scrap market. Imported aluminum scrap is sometimes used by secondary smelters under favorable market conditions.

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<sup>4</sup> This total probably includes plants dedicated to UBC remelting.

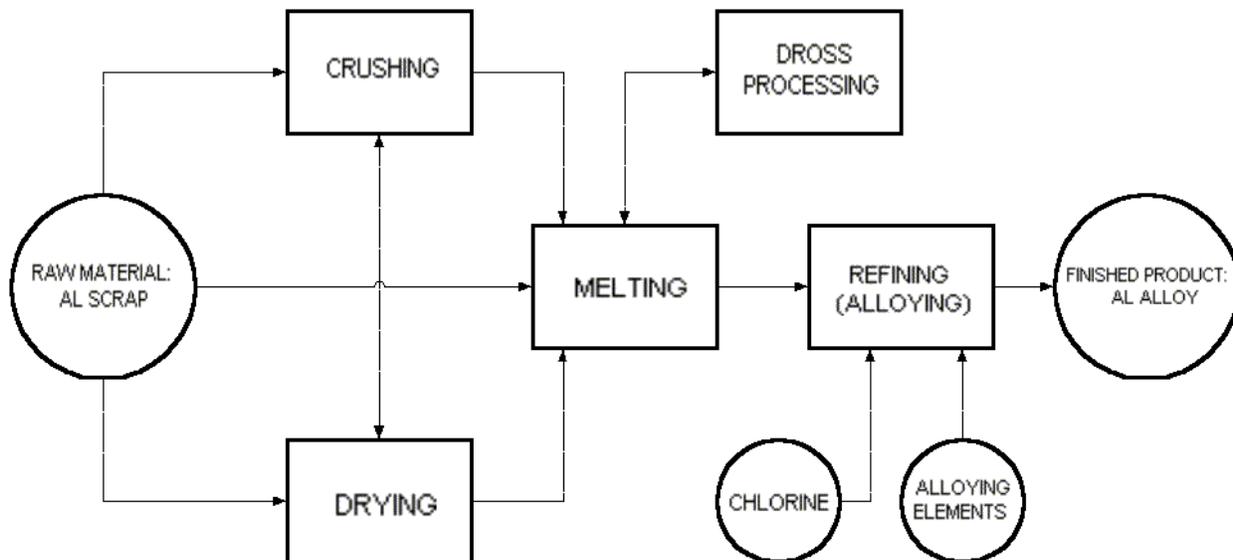


Figure B-1. Typical Secondary Aluminum Smelter Flow Diagram (after Viland 1990)

Scrap is generally shipped to secondary smelters in trucks with 45,000-lb (20 t) capacity. Rail shipment is also used. Scrap yard operations are illustrated in Figure B-2.

As indicated in Figure B-1, crushing (or shredding) may be required for size reduction prior to melting. A shredder at a secondary aluminum smelter is shown in Figure B-3. During the sizing operation, discrete iron contaminants are magnetically separated. The scrap may be dried to remove moisture and organic contaminants such as cutting oils and plastics. Rotary kilns with baghouse dust collection systems are often used for this operation.

Some smelters have fixed radiation detection systems installed to monitor incoming and outgoing materials for radioactive contamination, some use hand-held detectors, and some do not monitor but rather rely on their suppliers to ensure against inadvertent contamination. Potash (KCl), a fluxing agent, can trigger radiation detection systems due to naturally-occurring K-40.

Occasionally, a small scrap dealer may melt some of the scrap into ingot for sale to a larger scrap dealer if the economics are appropriate (i.e., the value of the remelt ingots is greater than the value of the unprocessed scrap plus the cost of melting the scrap into ingots). Such an operation might involve a small gas-fired pot furnace with a fume collection hood which vents to the atmosphere. During operation at such a facility, an americium source was inadvertently melted. The incident was detected when the ingot was delivered to a larger dealer with radiation



Figure B-2. Handling of Scrap Turnings from Forged Aluminum Auto Wheels at IMCO's Uhrichville OH Plant (IMCO 1997)

monitoring equipment. Apparently, cleanup after the incident was reasonably straightforward in that most of the Am remained with the aluminum and was not spread around the facility (Mobley 1999).

A description of the features of several secondary smelters is included in Appendix B-1. Appendix B-2 provides a detailed description of the secondary smelter operations at

Arkansas Aluminum Alloy Inc. in Hot Springs (Kiefer et al. 1995).



Figure B-3. Scrap Shredder at Secondary Aluminum Smelter

#### B.4.2 Melting Practice

Melting for general scrap recovery is done almost exclusively in gas- or oil-fired reverberatory furnaces, typically of 40,000 to 220,000-lb (18 to 40 t) capacity (Viland 1990). Halide salts (such as mixtures of NaCl, KCl, and NaF) are added to form a cover over the melt and reduce oxidation. For casting alloys, Si (2% to 13%) is added in secondary smelting process to promote casting alloy fluidity. (Silicon also imparts other desirable properties such as wear resistance.) Die casting alloys generally can accept higher limits on Fe, Mn, Cu, Zn, and Cr. For corrosion resistance (e.g., outboard motors), copper limits "are greatly reduced." Permanent mold and sand casting alloys must have reduced Fe levels to improve ductility (Viland 1990).

The melting cycle for a typical reverberatory furnace consists of charging scrap into the forewell of the furnace, blending and mixing alloying materials, addition of fluxing salts, magnesium removal, gas removal, skimming off the dross, and pouring. A heel consisting of 20 to 40% of the furnace capacity is generally left in the furnace to shorten the melting cycle (Plunkert 1995). Scrap is charged into the furnace, either with a front-end loader or a belt conveyor, over a 16- to 18-hour period. Magnesium and gas removal require two to four hours and tapping requires an additional three to four hours resulting in a total cycle of about 24 hours.

According to Crepeau et al. (1992), drossing fluxes typically constitute about 0.2% to 1% of the metal charged<sup>5</sup>. Use of NaF in the flux will add traces of Na to the melt;  $K_2TiF_6$  can be used to add Ti, and  $KBF_4$  can be used to add B.  $AlF_3$  will tend to remove Ca, Sr, and Mg, while chlorine-releasing compounds promote removal of Mg, Na, and Sr. Phosphorus can be added to the melt via flux containing amorphous phosphorus.

Prior to tapping the furnace, the melt is typically treated with chlorine gas to reduce magnesium to acceptable levels<sup>6</sup>. During this "demagging" process, other metallic impurities which form chlorides more stable than  $AlCl_3$  are also removed from the melt and transferred to the dross. Hydrogen is also removed but, for that impurity, removal is by solubility in the  $Cl_2$  gas rather than by HCl formation.

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<sup>5</sup> It should be noted that this is the amount of flux charged not the amount of dross produced, the latter being much higher.

<sup>6</sup> Magnesium is not undesirable in all alloys. Some aluminum alloys contain up to 10% Mg.

Neff notes that alkali and alkaline earth metals such as Li, Na, K, and Ca can be removed from aluminum either by chlorine injection of pot-line vessels or in-line degassers (Neff 1991).

Furnace output is typically cast into ingots or sometimes into sows (1,000-lb cast blocks). In North America, about 500 million lb/year is shipped in liquid form in crucibles via trucks (Viland 1990). Truck shipment of molten aluminum is shown in Figure B-4.



Figure B-4. Aluminum Liquid Metal Transporter

During the melting cycle, dross is skimmed from the melt surface and collected in containers adjacent to the furnace. Dross is processed to recover the contained aluminum by physical separation using hammer mills or by melting in rotary salt furnaces. Some secondary smelters use rotary furnaces, particularly for the processing of low-grade or light scrap.

“For every 1 million pounds of scrap processed, 760,000 pounds of secondary aluminum is produced, and 240,000 pounds of dross residues, and 3,000 pounds of baghouse dusts are generated. The dross residues are not hazardous but contain salts and are generally disposed of in solid waste landfills” (Viland 1990). Salt recovery systems have not been very successful because of the extremely corrosive nature of the salts. Baghouse dusts may contain Cd and Pb above the limits of the EPA Toxicity Characteristics Leaching Procedure (TCLP) test. In many cases, these dusts are disposed of in hazardous waste landfills.

### B.4.3 Dust Handling

Not all secondary aluminum smelters use baghouse dust collection systems. Those that do may not process all of the furnace offgas through the baghouse. For example, at one smelter, each furnace has a canopy exhaust system which is connected to a baghouse for dust collection. About 40% of the flue gases is also exhausted through the baghouse to maintain the gas temperature above its dew point. Condensation of halides can cause severe corrosion problems in the exhaust system. The balance of the flue gases is exhausted directly through the stack. The baghouse has eight modules. Lime-coated bags are used because of the acidic nature of the offgas. Dust collected from blowdown is accumulated in the baghouse hoppers and transported via screw conveyors to reinforced plastic bags attached to the ends of the enclosed conveyors. The filled plastic bags are temporarily held in a nearby commercial steel dumpster and ultimately taken by the disposal contractor to an approved municipal landfill. A maintenance operator typically spends about one hour per day in the baghouse area. The fabric filter bags are replaced every two years.

Although some hazardous volatiles accumulate in the dust, the collected waste at this smelter meets EPA TCLP requirements. (TCLP results are summarized in Table B-6.) Cadmium in the dust may come from paint while multiple sources of lead are possible. Comparison of the crusher fines and the furnace dust data suggests that the furnace dust is enriched in the volatile elements Cd and Hg and depleted in Ba and Cr.

Some data on airborne dust concentrations have been obtained from a small aluminum foundry where three electric furnaces were used to melt aluminum under chloride/fluoride fluxes. The molten aluminum was transferred to a ladle and then poured into steel molds (Michaud et al. 1996). Dust samples were collected at fixed sampling locations: between two of the furnaces, near the core maker, next to a mold, and in the middle of the foundry room. The average total dust concentration was 2.5 mg/m<sup>3</sup> and the respirable concentration was 1.1 mg/m<sup>3</sup>. The respirable fraction, as defined by the American Council of Governmental and Industrial Hygienists (ACGIH 1996), has a range of particle aerodynamic diameters (AD) with a median value of 4 μm. The total dust concentration included an average of 0.05 mg/m<sup>3</sup> of Al and 0.03 mg/m<sup>3</sup> of Mg. Using SIMS and XPS analytical probe techniques, Ca and Si were found to be associated with the coarse fraction (i.e., >4μm AD) and S, Zn and Cl were concentrated in the fine particles. Na, K, Al and C exhibited higher intensities in the fine fraction (i.e., <1 μm AD) than in the coarse fraction. Fluorine was strongly detected in all size fractions.

Table B-6. TCLP Values for Dust Samples and Spent Refractory (mg/L)

Element	TCLP Limits	Furnace Dust	Crusher Fines	Spent Refractory <sup>a</sup>
As	5	<0.70	<0.70	<0.70
Ba	100	0.42	0.78	1.2
Cd	1	0.08	0.023	0.054
Cr	5	<0.010	0.023	0.87
Pb	5	<0.2	<0.2	<0.2
Hg	0.2	0.003	<0.0004	<0.0004
Se	1	<0.7	<0.7	<0.7
Ag	5	<0.01	<0.01	<0.01

<sup>a</sup> Solid material, not dust

Additional dust sampling results are available from a NIOSH study at the Arkansas Aluminum Alloys Inc. smelter which uses three 220,000-lb (100 t) reverberatory furnaces (Keifer, et al. 1995). Prior to the referenced study, area samples collected in 1992 showed *respirable* dust concentrations of 2.3 mg/m<sup>3</sup> near furnace #2 and 4.4 mg/m<sup>3</sup> near furnace #4. Earlier samples taken in 1989 found 12.17 mg/m<sup>3</sup> of *total* dust at the scrap conveyor and 15.38 mg/m<sup>3</sup> of *total* dust at the baghouse. In the referenced 1995 study, NIOSH took samples in a variety of locations that were analyzed for total dust and component metals. Details, including time-weighted average (TWA) concentrations, are presented in Table B-7.

No Cr, Pb, nor Ni was detected in the samples collected. In two samples, Cd was reported between the analytical detection limit and the limit of quantification. Although not so stated by the authors, other values in the table, which appear in parentheses, presumably fall within the same range—i.e., measurements were made, but the values are so low as to be suspect.

#### B.4.4 Partitioning of Contaminants

##### B.4.4.1 Thermochemical Considerations

This section examines the expected partitioning of contaminants during the melting process. As noted above, the primary radioactive contaminants in DOE aluminum scrap are expected to be U, Tc, Np, Th, and Pu. Some of these elements may be transferred to the dross during the demagging operation, depending on the relative thermodynamic stability of the respective chloride species.

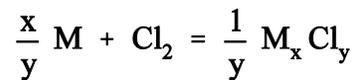
Table B-7. Secondary Aluminum Smelter Dust Levels

Activity Sampled	Sampling Time (min)	Total Dust (mg/m <sup>3</sup> )	TWA <sup>a</sup> Concentration (µg/m <sup>3</sup> )							
			Al	Zn	Cd	Mg	Mn	Fe	Cu	Ti
Skimming/pouring - Furnace #2	366	0.45	40		(0.2) <sup>b</sup>	(2.9)	0.16	6.3	0.8	1.6
Skimming/pouring - Furnace #2	364	0.26	18			(2.4)		2.5	0.4	0.6
Furnace #4 operator - South side	463	0.64	57	0.1		5.5	0.2	19	1.5	0.8
Furnace #4 operator - North side	480	0.46	12	3.1		(2.4)		4.0	0.6	0.18
Furnace #2 operator - South side	486	0.62	50	2.3		4.8	0.44	10	1.5	0.48
Furnace #2 operator - North side	420	0.55	37	1.9		8.8	(0.1)	12	1.4	0.4
General area - sweeping/cleaning	118	0.60	27	7.7	(0.3)	(5.1)		8.9	2.0	0.9
Pouring area - sweeping/cleaning	125	3.24	370			12	5.2	49	1.9	21

<sup>a</sup> Time-weighted average

<sup>b</sup> Values in parentheses are assumed to be less than the lower quantification limit

Representative values for the free energy of formation for the following reaction at 1000 K (a typical pouring temperature for aluminum) are presented in Table B-8.



Assuming that the above equation represents the governing chemistry, that equilibrium is obtained and that the dilute solutions behave as pure substances, it is assumed that all the elements below AlCl<sub>3</sub> in Table B-8 will be transferred to the dross and that those above AlCl<sub>3</sub> will tend to remain with the aluminum. Hydrogen (tritium) should also be substantially but not totally removed from the melt and released to the atmosphere. As noted previously, hydrogen removal is by solution in the chlorine rather than by HCl formation, which is thermodynamically unfavorable. Thermodynamic equilibria based on pure substances suggest that solute elements with standard free energies of formation of the solute metal chlorides higher (less negative) than

that of  $\text{AlCl}_3$  will remain in the melt. However, there is virtually no information available on activity coefficients for the same substances in dilute solutions. Thus, the thermochemical calculations in Table B-8 provide only rough guidelines as to the expected partitioning during melting. It may be noted from Table B-8 that if protactinium is in the +5 valence state, it would be expected to remain in the melt but if it is in the +3 valence state it would be expected to partition to the dross. However, any pentavalent chloride which forms would be reduced by aluminum, so Pa should partition to the dross.

Many chlorides are volatile at low temperatures and this attribute may play a role in the partitioning process. Addition of chlorine to the melt for demagging and hydrogen removal might result in the formation of volatile chlorides. Selected metal chlorides with boiling points below the melting point of aluminum are listed in Table B-9.

The gas volumes passing through the liquid metal and the liquid flux can be large and three interactive partitioning mechanisms are possible—between the gas and the metal, between the gas and the flux, and between the flux and the metal. As suggested by Table B-9, many chlorides will have a perceptible vapor pressure at 1000 K and can be transferred from the melt to the gas. Some of these displaced chlorides will terminate in the dross and some in the fume which will either condense on the ducting or in the baghouse.

Removal of a portion of the iron and silicon, but not copper, has been observed during the treatment of aluminum melts with  $\text{Cl}_2$  in the laboratory. Iron and silicon chlorides condensed on the walls of the system ducting. The partitioning mechanism was not elucidated but may involve small partial pressures of the solute metal chlorides in a volatile aluminum chloride. The gaseous aluminum chloride is dense and is not transported a significant distance in the offgas system. These experiments involved large quantities of flux and highly specialized melting practices not representative of those expected in a secondary aluminum smelter. In a typical smelting operation, impurities such as iron are not preferentially removed.

Iron, Sb, Ce, Co, Nb, Sr, Th, and U have no reported solubility in molten aluminum; rather, they form intermetallic compounds which are in equilibrium with pure aluminum (Davis 1993). Thus, volatile chloride formation would require a reaction between chlorine and, say,  $\text{UAl}_4$ , rather than between chlorine and uranium dissolved in the aluminum. If a volatile chloride did form with an impurity less stable (per Table B-8) than  $\text{AlCl}_3$ , it would most likely be immediately reduced before it could exit the melt.

Table B-8. Standard Free Energy of Formation ( $\Delta F^\circ$ ) for Various Metal Chlorides at 1,000 K

Metal Chloride	$-\Delta F^\circ$ (Kcal/g-atom Cl)
RuCl <sub>3</sub>	decomposes at 900 K
MoCl <sub>6</sub>	3.23
TcCl <sub>3</sub>	7.37
NbCl <sub>5</sub>	11.4
PbCl <sub>4</sub>	18.6
NiCl <sub>2</sub>	18.8
AgCl	19.1
CuCl	20.9
SbCl <sub>3</sub>	21.2
CoCl <sub>2</sub>	22.4
HCl	23.9
FeCl <sub>2</sub>	26.6
SiCl <sub>4</sub>	27.9
ZnCl <sub>2</sub>	32.2
MnCl <sub>2</sub>	40.1
PaCl <sub>5</sub>	41.3
<b>AlCl<sub>3</sub></b>	<b>45.5</b>
UCl <sub>3</sub>	53.5
NpCl <sub>3</sub>	55.2
MgCl <sub>2</sub>	57.4
ThCl <sub>3</sub>	58.9
PuCl <sub>3</sub>	59.4
PaCl <sub>3</sub>	63.9
AmCl <sub>3</sub>	66.6
SrCl <sub>2</sub>	82.6
CsCl	83.0

The possibility also exists that some elements expected to be transferred to the dross would also volatilize to some extent and either condense on the ducting or be collected in the baghouse dust. Based on Tables B-8 and B-9, uranium might be expected to exhibit such behavior.

Table B-9. Selected Metal Chlorides with Boiling Points Below 1000 K

Metal Chloride	Boiling Point (K)
AlCl <sub>3</sub>	453 (sublimes)
FeCl <sub>3</sub>	592
MoCl <sub>6</sub>	630
MnCl <sub>3</sub>	900
MnCl <sub>4</sub>	384
NbCl <sub>5</sub>	519
PaCl <sub>5</sub>	659
PbCl <sub>4</sub>	400
SbCl <sub>3</sub>	492
SiCl <sub>4</sub>	330
TcCl <sub>5</sub>	505
UCl <sub>5</sub>	690
UCl <sub>6</sub>	550

Source: Glassner 1957

Note: no information available on chlorides of Eu and Pm

While the simple free energy calculations presented in Table B-8 suggest that any U, Th, Pu, or Np dissolved in an aluminum melt will be removed by chlorine during the demagging process, the radioactive contaminants may be in the form of oxides. It is not clear whether such oxides will be either reduced by aluminum or converted to the halide form. For example, the thermodynamics are unfavorable for converting UO<sub>2</sub> to either a fluoride or chloride at 1,000 K. In addition, the free energy change for the reaction between UO<sub>2</sub> and Al to form Al<sub>2</sub>O<sub>3</sub> and U is about zero at 1,000 K, suggesting that this reaction is also unlikely to proceed. However, as will be discussed in Section B.4.4.2, formation of uranium-aluminum intermetallics has been observed.

#### B.4.4.2 Observed Partitioning

The partitioning of uranium in aluminum melts has been experimentally measured by Copeland and Heestand (1980). In this work, aluminum melts were equilibrated with a slag of unspecified composition containing 0.3 wt% uranium at 973 K and the uranium pickup by the aluminum was measured. Based on this type of laboratory measurement, the partition ratio—defined as the concentration of the uranium in the slag to the concentration in the metal—was determined to be

190. The experimental results, which suggest that some decontamination of the melt will occur, are in contrast to thermodynamic calculations made by these authors *for an oxide system* which suggested a value on the order of  $10^{-3}$  for the partition ratio<sup>7</sup>. In another set of experiments, these authors prealloyed uranium with aluminum and found that the partition ratio was only 2 to 3, as compared to 190 when uranium-containing slag was equilibrated with the molten aluminum.

Copeland and Heestand also examined drip melting, where surface-contaminated aluminum was placed on a metal screen and then heated to above the melting point. The molten aluminum dripped through the screen to a crucible below while the dross remained on the screen. In this experiment, the metal contained 16 ppm U while the dross contained 2,100 ppm U. When the drip melting process was scaled to multi-kilogram size ingots, the separation was less effective, with 4 ppm U in the aluminum and 25 to 75 ppm in the dross.

Heshmatpour and Copeland (1981) described additional laboratory measurements of uranium partitioning during aluminum melting. In these experiments, 500 ppm of  $\text{UO}_2$  was added to aluminum, and the melts were held at 1,573 K under various slags. Experimental results are summarized in Table B-10.

While the results generally show some preferential partitioning of uranium to the slag, there are some results which appear anomalous. Sample 5 shows very little decontamination even though companion tests (samples 3 and 4) with slightly different fluxes show much higher partition ratios. The flux compositions used for samples 1 and 18 are significantly different than would be expected in commercial secondary smelting. Except for sample 5, the uranium content of the melt ranged from about 1 to 100 ppm when halide or cryolite-type fluxes were used. It should also be noted that all of these tests were conducted at a substantially higher temperature than used in commercial secondary smelting. It is not clear from this work what effect the higher temperature has on the partition ratios.

However, a study by Uda et al. (1986) showed that the residual uranium content in aluminum melts doped with 500 ppm U increased as the melting temperature increased. The melting was conducted under a flux of 14% LiF-76% KCl-10%  $\text{BaCl}_2$  and the mass of the flux was 10% of

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<sup>7</sup> This partition ratio is based on the reaction of uranium in the aluminum melt with  $\text{Al}_2\text{O}_3$  in the slag to produce  $\text{UO}_2$  in the slag. The calculation assumes that the weight of the slag is 10% that of the melt, that the thermodynamic activity of  $\text{Al}_2\text{O}_3$  in the slag is 0.1, that the activity of  $\text{UO}_2$  in the slag is 0.01, and that the Henry's Law constants for U in the aluminum melt and  $\text{UO}_2$  in the slag are unity.

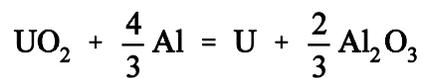
that of the metal charge. The residual uranium content of alloy 5083, containing 4.45% Mg, increased from about 1 ppm at 800°C to about 10 ppm at 1000°C. For alloy 1050 (99.5%Al), the residual uranium content increased from about 20 ppm to about 70 ppm over the same temperature range. The experimental program showed that the uranium removal increased exponentially with increasing magnesium content in the aluminum.

Table B-10. Partitioning of Uranium in Aluminum Melts in Zirconia Crucibles at 1573 K

Sample	Metal (g)	Flux (g)	UO <sub>2</sub> (ppm)	Uranium (ppm)		Partition Ratio <sup>a</sup>	Flux (%)							
				Metal	Slag		AlF <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	CaF <sub>2</sub>	CaO	Fe <sub>2</sub> O <sub>3</sub>	NaF	SiO <sub>2</sub>	
1	76	7.6	500	1.2	9610	801				100				
2	81	8.1	500	111	1360	1.2							100	
3	81	8.1	500	0.9	405	45				60			40	
4	80	8.0	500	2.4	570	24				40			60	
5	78	7.8	500	315	150	0.05				20			80	
6	50	0	500	469			No flux							
7	50	0	500	430			No flux							
8	166	8.3	500	31.4	1760	3	35	10					55	
9	503	25.15	500	81.1	4190	3	35	10					55	
18	250	25	500	308	255	0.08		10	5	50	5			30

<sup>a</sup> Amount of contaminant in the slag divided by amount of contaminant in metal

The experimental observation that uranium removal from aluminum increases as the temperature decreases is opposite of that which is predicted from the calculated equilibrium constant for the reaction:



No satisfactory explanation was provided by the authors for the difference between the experimental observations and the thermodynamic calculations. The increased uranium removal associated with higher magnesium content is attributed to the formation of strong intermetallic compounds between Al and Mg which reduce the ability of the aluminum to reduce the UO<sub>2</sub>. This argument appears specious since all of the aluminum is not tied up as intermetallics.

In a subsequent paper, Uda et al. (1987) described the electroslag melting of aluminum alloy 5052 under a flux of 14% LiF, 76% KCl and 10% BaCl<sub>2</sub>. The aluminum alloy electrode was contaminated by drying a solution of known uranium concentration on the surface. The amount

of uranium was such that the concentration in the finished ingot would be 500 ppm if none were lost to the slag or elsewhere. The actual uranium concentration in the finished ingot was 3 to 5 ppm. Insufficient information is provided by the authors to calculate a partition ratio.

Mautz et al. (1975) described the results of melting some aluminum scrap from the Portsmouth gaseous diffusion plant in a oil-fired reverberatory furnace of unspecified size. Fluxing agents were not used. The aluminum scrap consisted of die-cast, wrought, and cast parts which had extended exposure to  $UF_6$ . The scrap was chemically decontaminated prior to melting. Sixty-two ingots from die cast scrap contained residual uranium ranging from a minimum of 0 to 100 to a maximum of 1300 to 1400 ppm. (Since bar charts rather than actual data were provided by the authors, only ranges for the minimum and maximum could be determined.) Ingots produced from cast and wrought scrap were generally lower in uranium than ingots produced from die-cast scrap.

Some experimental work has shown that  $UO_2$  can react with Al in the solid state at temperatures of 873 K to form various intermetallic compounds such as  $UAl_2$ ,  $UAl_3$ , and  $UAl_4$  (Waugh 1959). Reaction between  $UO_2$  and Al to form  $UAl_x$  and  $Al_2O_3$  was 90% to 100% complete in 10 hours. The U-Al binary phase diagram predicts that the equilibrium phases formed during the solidification of melts containing small quantities of uranium should be  $UAl_4$  (or  $U_{0.9}Al_4$ ) and aluminum (Davis 1993). If the same reaction occurs in the liquid state, it would tend to promote partitioning of the uranium to the melt (as  $UAl_x$ ) rather than to the slag (as  $UO_2$ ).

Heshmatpour et al. (1983) described one experiment where 500 ppm of  $PuO_2$  was melted with 100 g of Al at 800°C without any flux. The solidified sample contained 5.4 ppm Pu while the surface Pu concentration was 18,300 ppm. These results suggest that if plutonium is present as the oxide it is likely that most of it will be removed with the dross.

As noted under B.4.4.1 above, oxide, as well as chloride, reactions can occur between elements and compounds in the melt and in the slag. Hryn et al. (1995) have measured the cation content of the oxide residue of dross generated by melting series 3XX aluminum casting alloys. (These oxide residues were byproducts of the process of aluminum recovery from the dross.) The results are summarized in Table B-11. These measurements indicate that some of the metals which would be predicted to partition to the melt on the basis on Table B-8 are also found in the dross. These include silicon, zinc, copper, manganese, and iron.

Table B-11. Cation Impurities in 3XX Aluminum Residue-Oxide Samples

Element	3XX Residue-Oxide (%)
Mg	4.7
Si	5.3
Ca	1.4
Ti	0.3
Zn	0.3
Mn	0.14
Fe	1.5
Cu	0.5

#### B.4.4.3 Baghouse Dust

As noted earlier, not all secondary aluminum smelters use baghouse dust collection systems. Some of those that do may collect only a portion of the offgas and pass it through the baghouse. Limited data are available to predict the partitioning of particular elements to the dust. As part of the EPA program to develop an air emissions standard for secondary aluminum smelters, some measurements have been made of the composition of the dusts based on stack samples. During the standards development program, two sets of particulate samples were taken from a furnace at the Alcan Recycling Facility in Berea, Ky. (U.S. EPA 1990). No information was provided on the composition of the metal being melted, so it is not possible to develop a detailed estimate of the how the various elements partition to the dust. However, if one assumes that the material being melted in alloy 3004—the standard material used for the aluminum can bodies (Davis 1993)—some insight into partitioning can be derived. Table B-12 compares the composition of alloy 3004 with the furnace particulate matter. From this table it can be seen that the particulates are enriched in magnesium and iron, depleted in manganese and essentially unchanged in zinc. Small quantities of other elements including Sb, Ba, Co, Pb, and Ni, were also found in the particulate matter. The limited information available does not suggest that particular elements have orders of magnitude concentration increases in the dust. Consequently, it is assumed that the dust has the same composition as the scrap with regard to metallic elements. Any particulates released to the atmosphere are also assumed to have the same metallic composition as the scrap.

Table B-12. Composition of Particulate Matter From Secondary Aluminum Smelter

Element	Alloy 3004 (%)	Alcan Furnace (Run 1)		Alcan Furnace (Run 2)	
		lb/hr	%	lb/hr	%
Al		3.19e+00		6.79e-01	
As	a	5.07e-04	0.016	<2.10e-04	<0.032
Ba	a	1.69e-02	0.53	<7.00e-03	<1.0
Cd	a	2.11e-04	0.0066	7.00e-05	0.010
Co	a	4.22e-04	0.013	<2.80e-05	<0.0041
Cr	a	1.44e-03	0.045	6.30e-04	0.093
Fe	0.70 max.	6.36e-02	2.0	3.54e-02	5.2
Hg	a	8.45e-05	0.0026	7.00e-05	0.010
Mg	0.8 to 1.3	9.38e-01	29	9.38e-01	138
Mn	1.0 to 1.5	5.07e-04	0.016	1.05e-03	0.15
Ni	a	<1.69e-03	<0.053	<1.40e-03	<0.21
Pb	a	1.69e-03	0.052	7.00e-04	0.10
Sb	a	3.38e-03	0.11	2.80e-03	0.41
Se	a	1.69e-04	0.0052	1.40e-04	0.021
Ti	a	<6.76e-02	<2.1	<5.60e-02	<8.2
Zn	0.25 max	1.02e-02	0.32	1.89e-03	0.28

<sup>a</sup> All other elements limited to 0.05% max. and 0.15% total

#### B.4.4.4 Proposed Partitioning

Based on the information presented here, coupled with technical judgement, the suggested partitioning ratios for the various elements between melt, dross, baghouse dust, and the atmosphere are summarized in Table B-13. Since the data are limited and conflicting, ranges are proposed in many cases. In the case of the uranium partition ratio, the very low and very high values in Table B-10 were discarded and it was assumed that the partition ratio could vary from 1 to 100. In the absence of other information and based on the assumption of similar chemical and thermodynamic behavior, this same range was assigned to Ac, Am, Ce, Eu, Np, Pa, Pm, Pu, Ra, and Th. The possibility also exists that some uranium which partitions to the dross could volatilize and collect in the baghouse dust. Where no experimental evidence exists to the contrary, partitioning is assumed to follow predictions based on the thermodynamic calculations in Table B-8 (e.g., Cs, and Ag). In some instances the calculations in Table B-8 were tempered

by the observations on oxides in the dross included in Table B-11. In applying the data in Table B-11, Ni and Co were assumed to be analogous to Fe and Nb to be analogous to Ti.

Additional comments on various alloying elements are summarized below (Davis 1993):

- silver has substantial solubility in both liquid and solid aluminum
- lead has very limited solubility in both liquid aluminum (0.2 at%) and solid aluminum (0.02 at%) but lead is sometimes added to certain alloys to improve machinability
- carbon is occasionally found in aluminum as an oxycarbide or a carbide ( $Al_4C_3$ ), although fluxing operations usually reduce C to the ppm level
- antimony is present in trace amounts in primary commercial-grade aluminum and is used as an alloying element in certain aluminum alloys
- cobalt has been added to some Al-Si alloys containing iron to improve strength and ductility
- cerium has been added to experimental casting alloys to increase fluidity and reduce die sticking
- manganese is a common impurity in primary aluminum and is a frequently used alloying additive
- strontium is found in trace amounts in (0.01 to 0.1 ppm) in commercial aluminum
- molybdenum is a low level impurity in aluminum (0.1 to 1 ppm) and has been added as a grain refiner
- nickel has limited solubility in aluminum (0.04%) but nickel has been added to Al-Si alloys to increase hardness and strength at elevated temperatures

Table B-13. Proposed Partitioning of Selected Elements During Secondary Aluminum Smelting

Element	Partition Ratio (PR) (%)				Comments
	Metal	Dross	Baghouse <sup>a</sup>	Atmos. <sup>b</sup>	
Ac	1/50	99/50			1 < PR < 100
Ag	100				Table B-8, Davis 1993
Am	1/50	99/50			1 < PR < 100
C	1/10	99/90			Davis 1993
Ce	1/50	99/50			1 < PR < 100, Davis 1993
Co	99/90	1/10			Tables B-8, B-11 (same as Fe), Davis 1993
Cs		100			Table B-8
Cu	99/90	1/10			Tables B-8, B-11
Eu	1/50	99/50			1 < PR < 100
Fe	99/90	1/10			Tables B-8, B-11
I		50/100		50/0	
Mn	99/90	1/10			Table B-8, B-11, Davis 1993
Mo	100				Table B-8, Davis 1993
Nb	99/90	1/10			Tables B-8, B-11 (same as Ti)
Ni	99/90	1/10			Tables B-8, B-11 (same as Fe), Davis 1993
Np	1/50	99/50			1 < PR < 100
Pa	1/99	99/1			Table B-8
Pb	100				Table B-8, Davis 1993
Pm	1/50	99/50			1 < PR < 100
Pu	1/50	99/50			1 < PR < 100
Ra	1/50	99/50			1 < PR < 100
Ru	100				Table B-8
Sb	100				Table B-8
Si	99/90	1/10			Tables B-8, B-11
Sr	1/10	99/90			Table B-11, Davis 1993
Tc	100				Table B-8
Th	1/50	99/50			1 < PR < 100
U	1/50	99/50			1 < PR < 100, volatile Cl <sup>-</sup>
Zn	99/90	1/10			Tables B-8, B-11

<sup>a</sup> Baghouse dust is assumed to have the same composition as metal.

<sup>b</sup> Proposed EPA air emissions standard for secondary aluminum smelters is 0.4 lb of particulate material per ton of furnace charge. This material is assumed to have the same composition as the metal.

In Table B-13, it is assumed that a significant portion of any iodine will combine with cationic species in the halide slag. Some iodine may escape up the stack as I<sub>2</sub> gas. The proposed partitioning of this element is based solely on technical judgement. Data in Table B-9 suggest

that some uranium may concentrate in the dust due to condensation of a uranium chloride volatilizing from the slag, but insufficient information is available to quantify this possibility.

#### B.4.5 Dross Processing

Significant concentrations (10% - 80%) of aluminum are found in the dross, necessitating reprocessing of this waste stream for maximum metal recovery. One of two techniques is generally used for dross processing:

- physical separation
- melting in rotary salt furnaces

When physical separation is employed, the dross is passed through hammer mills and across screens. The screen oversize, which is rich in aluminum, is returned to the smelting process while the undersize, containing primarily salt and some oxides, is shipped to a landfill. Some landfills may have leachate liners. Dross processing may be done on site or at a dedicated facility. In some cases, the dross is sold to a processor and the recovered aluminum is repurchased.

Rotary furnaces produce larger quantities of salt waste (salt cake) which contains relatively small amounts of aluminum as compared to dross. It has been estimated that recovery of aluminum from skim and dross in rotary furnaces generates about 460,000 t of salt cake annually. The salt cake contains 5 to 7 wt% aluminum, 10 to 50 wt% salts, and 30 to 85 wt% residue oxides. The residue oxide is primarily aluminum oxide with minor amounts of cryolite, magnesium oxide, magnesium aluminate, and other contaminants (Graziano et al. 1996). Most of the salt cake is landfilled. Given long-term concerns about landfill availability, processes are being developed to reduce the quantity of salt cake which must be buried. The Ford Motor Company has initiated a process to handle about 11,000 t of aluminum salt cake annually from their foundry in Essex, Ontario. The salt cake will be shipped by Browning Ferris Industries to a facility in Cleveland for processing by the Aluminum Waste Technology, Inc. Aluminum and salt are recovered from the process and sold to secondary smelters, while aluminum oxide is recovered and sold to the steel industry for topping compounds (Wrigley 1995).

Aluminum Waste Technology, Inc., is a wholly owned subsidiary of Alumitech, Inc (which is, in turn, owned by Zemex Corporation). Alumitech, Inc. is also seeking other markets for the metallic oxides recovered from the process, which it describes as non-metallic products (NMP).

To further this product strategy, Alumitech has built a metallurgical plant in Cleveland to prepare NMP feedstock for the production of refractory ceramic fiber (Zemex 1998). Calcium aluminate is also recovered as a separate product for use as a steel slag ingredient. Because of European landfill restrictions, dross from Austria is being shipped to Alumitech for processing (“Aluminum Smelters Export” 1995).

Graziano et al. (1996) evaluated the economics of various salt cake recycling options. Their base case design was predicated on combining processes that had been commercialized, licensed, or developed by the industry. The base case process is described as follows (see Figure B-5):

In the solids preparation section, the salt cake is dry-crushed, screened, and magnetically separated to recover an aluminum-rich, iron-free product for remelting in a secondary aluminum furnace. We assumed that 70% of the aluminum in the salt cake is recovered in this byproduct stream at 50% purity. The effluent from the solids preparation section is salt cake, depleted in aluminum and crushed to 1-mm size, for feed to leaching.

In base case process, crushed salt cake from the solids preparation section is fed to a leaching tank, where the salts are dissolved in water at ambient conditions (25°C, 1 atm) to yield a brine concentration of 22 wt% salts. Insolubles (aluminum oxide) in the leach effluent are separated from the brine and washed with water to remove residual salts. The wet oxide is landfilled or further processed for sale.

The clarified brine solution is fed into a forced-circulation evaporator system designed for energy recovery (single effect with vapor recompression or multiple effect). The NaCl and KCl salts crystallize as the water is evaporated. The slurry effluent from the evaporator is then routed to product recovery.... In the product recovery section the salt solids are separated from the brine solutions with a centrifuge and then dried and stored for sale.... The filtrate from the centrifuge is then recycled back to the evaporator to maximize recovery of salts.

The gas treatment section is required to control emissions of toxic and explosive gases generated when salt cake is leached in water. According to European sources, hydrogen, ammonia, methane, phosphine, and hydrogen sulfide are emitted from the leaching action. ...the gas treatment section consists of a thermal oxidizer followed by a chlorine scrubber.

The authors modeled a plant which processed 30,000 t of salt cake per year with a 90% on-stream factor. The salt cake was assumed to contain 6 wt% Al, 14 wt% NaCl, 14 wt% KCl, and 66 wt% aluminum oxide. Assuming that a 20% return on investment was needed, the base case plant had a negative net present value, indicating lack of economic viability. They also

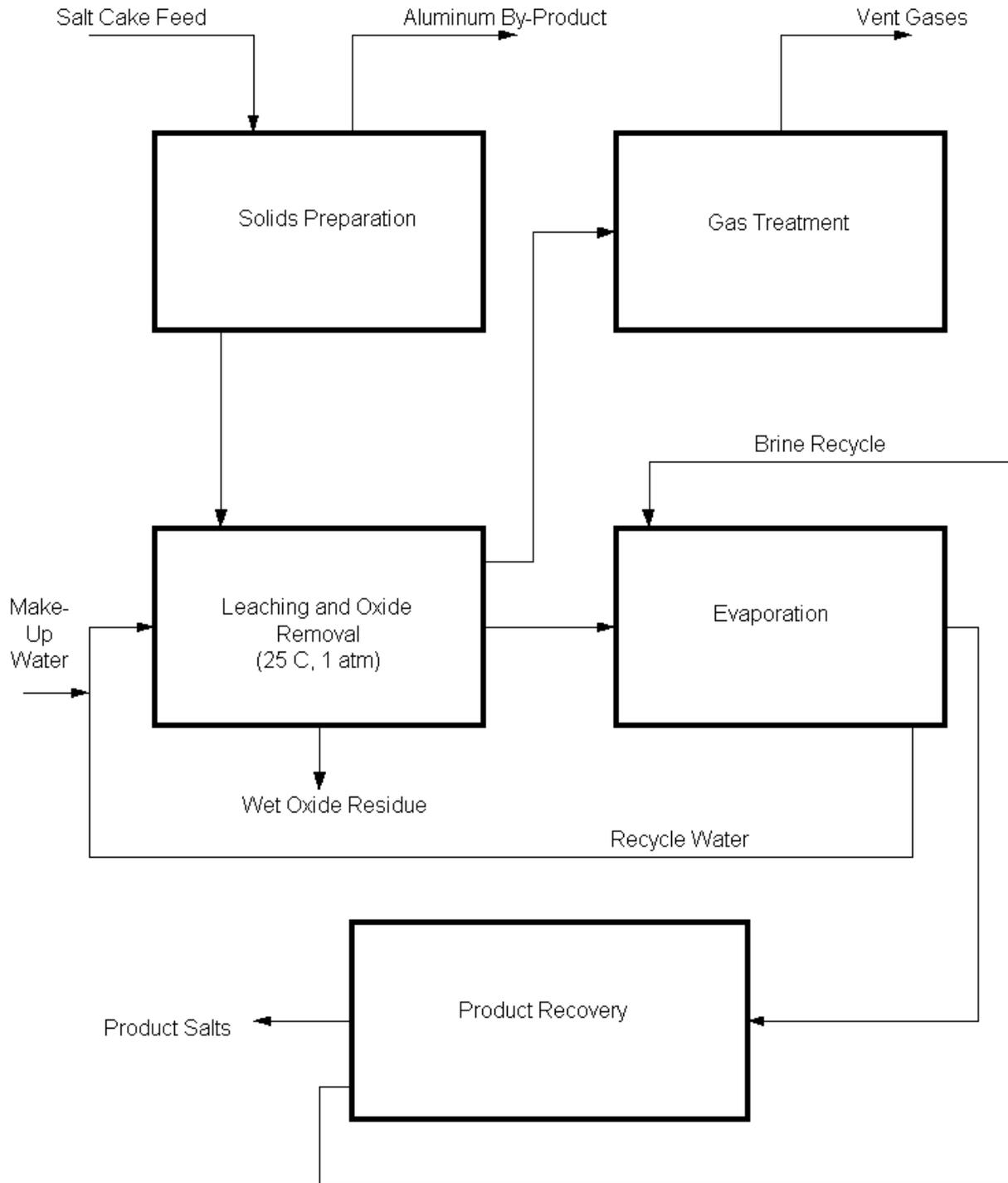


Figure B-5. Proposed Salt Cake Recycling Process (Graziano et al. 1996)

considered alternative flow sheets involving high temperature leaching of the salt cake followed by flash crystallization, a solvent/anti-solvent process to replace evaporation, and the use of

electrodialysis to replace evaporation. None of these alternatives was economically viable. The base case process could be made more attractive if the scale of the operation were increased and if the aluminum oxide residue were recovered for sale rather than landfilled. Higher landfill costs also improve process economics. However, producing a marketable product would probably require additional processing to meet specifications for selected applications.

Graziano et al. (1996) were aware of only three operations in the United States where salt cake recycling was practiced. These included Aluminum Waste Technology (Cleveland), Reynolds Metals Company (Richmond, Va.), and Insamet (Litchfield Park, Ariz). Salt cake recycling is more prevalent in Europe, driven by landfill restrictions.

More recently IMCO Recycling Inc. (1998) has described the process at the Litchfield, Ariz. plant, which is 70% owned by IMCO. The plant recycles aluminum scrap and turnings under tolling arrangements. It also processes concentrates from purchased dross and salt cake in a patented wet milling process. The recovered aluminum is melted and sold on the open market. Aluminum oxide, which is a byproduct of the wet-milling process, is sold for use in making Portland cement. The salt will be recovered from evaporation ponds and some will be used as flux in IMCO's aluminum smelting operations. At its Utah facility, IMCO operates a joint venture with Reilly Industries where salt cake is recycled into aluminum concentrates, aluminum oxide, and brine. The brine is transferred to a solar recovery system operated by Reilly Industries. The recovered salts are used for a variety of purposes including fluxes.

While salt cake recycling is not widely practiced, the salt cake may be mechanically treated to remove a portion of the residual aluminum prior to landfilling the treated salt cake. Roth (1996) characterizes "standard existing technology" as involving a primary jaw crusher and a high-speed, horizontal shaft, plate-and-breaker-bar impact mill. This system produces a concentrate containing 60 - 70% aluminum from salt cake initially containing 3-10% aluminum.

#### B.4.6 Handling Baghouse Dust

Not all furnaces have baghouse dust collection systems. If such systems are used, baghouse dust is shipped to landfills for disposal or buried in landfills on site. The dust may contain lead and consequently stabilizing agents may be added to insure that the product meets the EPA TCLP requirements. Because of the demagging operations, many trace radionuclides will be converted to chloride salts which are non-volatile and will remain with the dross. As such, the potential for

radionuclides to concentrate in the baghouse dust is markedly lower at an aluminum smelter than at an EAF shop where steel is melted.

The EPA has recently proposed, under 40 CFR Part 63, to regulate emissions of hazardous air pollutants from secondary aluminum production. The proposed rule requires that particulate emissions be limited to 0.4 lb/ton and that HCl emissions be limited to 0.40 lb/ton (or be reduced by 90%). The proposed standard is based on achievable emissions limitations when melting dirty charge materials with unlimited fluxing and collecting the emissions in a fabric filter baghouse with continuous lime injection. However, the required limits can be achieved with other means, such as improved work practices, reduced flux usage, process design changes, etc. In the proposed standard, total particulates are measured as a surrogate for hazardous particulates and HCl is measured as a surrogate for HCl, HF, and Cl<sub>2</sub>.

#### B.4.7 Product Shipments

As noted above, approximately 230,000 t/y of remelted aluminum is shipped in the molten state. This is roughly 7% of all aluminum alloy shipments (based on a calculated metallic recovery of 3,190 million t in 1995 [Plunkert 1997a]). Hot aluminum is shipped in covered crucibles mounted on flatbed trucks (see Figure B-4). The crucible, which is typically made of 1.9-cm (0.75-inch) steel, is lined with approximately 13 cm (five inches) of refractory and contains 13.6 t of molten aluminum (Viland 1997). Haulage distances range from 35 to 250 miles. Hauling distances are limited to those within a five- to six-hour driving range.

### B.5 PRODUCT MARKETS

According to Viland (1990), markets served by secondary smelters are as follows:

- Direct automotive ..... 22%
- Automotive related ..... 44%
- Small engine ..... 8%
- Appliance ..... 7%
- Other ..... 19%

Another perspective on the output of secondary smelters is presented in Table B-14.

The total in Table B-14 is less than that in Table B-5. One reason for the difference is that Table B-14 does not include toll-processed aluminum beverage can stock. In addition, more estimation is involved in developing Table B-14 (Plunkert 1997b). From this table, it can be seen that most of the secondary smelter output is casting alloys. About 17% of the output is extrusion billets used to produce wrought alloys. These wrought alloys are based on new scrap of known, specific chemistry which can be remelted into compositions suitable for extrusion into various mill products (Plunkert 1999).

Table B-14  
Production of Secondary Aluminum Alloys by Independent U.S. Smelters in 1995 (t)

Secondary Product	Production
Die-cast Alloys	619,600
Sand and Permanent Mold Alloys	150,400
Wrought Alloys: Extrusion Billets	163,000
Aluminum-base Hardeners	5,400
Other <sup>a</sup>	39,600
Total	978,000
Less primary feedstocks (Al, Si, other)	120,000
Net Metallic Recovery	858,000

Source: Plunkert 1996

<sup>a</sup> Includes other die-cast alloys and other miscellaneous.

Additional detail on the wide variety of products produced from various aluminum casting alloys is included in Table B-15.

In addition to these applications, the steel industry uses about 450 million pounds (205,000 t) of aluminum each year as a deoxidant, and as an ingredient in slag conditioners and desulphurizers. Aluminum is also added to steels as a grain refiner. As an example of how this market is served, IMCO Recycling Inc. has plants in Elyria and Rock Creek, Ohio which process aluminum scrap. At these plants, presses, mills, and shredders are used for physical processing of dross and scrap. No melting is involved. The recovered aluminum is sold to about 70 customers. The majority of these customers blend the aluminum with other materials such as lime and fluorspar and sell the blended products to the steelmakers. Some of these blended products may be melted and cast at an IMCO facility in Oklahoma (IMCO 1997, IMCO 1998).

Table B-15. Representative Applications for Aluminum Casting Alloys

Alloy	Representative Applications
100.0	Electric rotors larger than 152 mm (6 in.) in diameter
200.0	Structural members: cylinder heads and pistons; gear, pump, and aerospace housings
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads
238.0	Sole plates for electric hand irons
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings
B295.0	Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts
332.0	Automotive and heavy-duty pistons; pulleys; sheaves
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings
354.0	Premium-strength castings for the aerospace industry
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts
357.0	Corrosion-resistant and pressure-tight applications
359.0	High-strength castings for the aerospace industry
360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges
380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
A380.0	Applications requiring strength at elevated temperature
384.0	Pistons and other severe service applications; automatic transmissions
390.0	Internal combustion engine pistons; blocks; manifolds; and cylinder heads
413.0	Architectural; ornamental; marine; and food and dairy equipment applications
A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
514.0	Fittings for chemical and sewage use; dairy and food handling equipment; tire molds
A514.0	Permanent mold castings of architectural fittings and ornamental hardware
518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
520.0	Aircraft fittings; railway passenger car frames; truck and bus frame sections
535.0	Instrument parts and other applications where dimensional stability is important
A712.0	General-purpose castings that require subsequent brazing
713.0	Automotive parts; pumps; trailer parts; mining equipment
850.0	Bushings and journal bearings for railroads
A850.0	Rolling mill bearings and similar applications

Compiled from *Aluminum Casting Technology*. American Foundrymen's Society. 1986.

Source: Davis 1993

## B.6 BASIS FOR EXPOSURE SCENARIOS

The information collected in the course of the present study of aluminum recycling can be used to construct a set of representative exposure scenarios for the radiological assessment of this process. The present section discusses possible scenarios and suggests one or more values for the exposure parameters. These data form the basis for the radiological assessment which is presented in Chapter 8.

### B.6.1 Exposure Parameters<sup>8</sup>

#### **Dilution**

Unlike carbon steel, movement of aluminum scrap is not geographically constrained by haulage costs. If all the DOE scrap available in 2003—7237 t, as listed in Table B-2—were melted in a single 220,000-pound (100 t) capacity reverberatory furnace with 100% scrap feed, a 25% furnace heel, and 90% on stream time, it would use 29 % of the furnace capacity under optimum operating conditions ( $7237 \div [100 \text{ t/d} \times 365 \text{ d/y} \times 0.9 \times 0.75] \approx 0.29$ ). Based on the April, 1997 operating rate for a specific smelter, a more realistic operating rate might be 47 million pounds (~21,000 t), in which case the DOE scrap would utilize 34% of the furnace capacity for one year. Since the specific smelter has four furnaces, three of which are typically in operation, the effective dilution in terms of worker exposure would be 0.11, assuming a separate crew for each furnace. But, if all the aluminum were melted in a single dedicated furnace, the dilution would be 0.34. Whether or not all the scrap would be handled in a single furnace would depend on the composition of the scrap, the scrap availability over time, and the product requirements at the particular time the scrap was processed.

As noted in Section B.4.2, some small furnaces may have a capacity limited to 40,000 lb (18 t) per year. It is not known whether a furnace of this size could be the only furnace at a facility or whether the facility would have multiple furnaces. It would require about 1.6 years to process the 7237 t of DOE aluminum through such a furnace. If the scrap consists of a variety of alloys, it is unlikely that it would be processed through a single furnace.

A plausible scenario for the limiting case is that all of the 2,527 t of aluminum from Paducah, available each year from 2016 to 2022, would be processed at the Wabash Alloys facility in

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<sup>8</sup> Data on a typical secondary smelter, presented in this section, is based on information from Graham (1997).

Dickson, Tenn. The capacity of this facility is about 150 million pounds (68,000 t) per year. In such a case, the contaminated scrap would represent about 3.7% total capacity mill of the mill—i.e., the contaminated scrap dilution factor would be 0.037.

### **Dross Production**

Dross production at a typical secondary smelter with reverberatory furnaces is about 15% of the metal charge and this dross contains 8 to 12% aluminum metal. The balance of the dross is halide salts and oxides. While this is typical for a specific smelter, as noted in Section B.4.4, some dross may contain as much as 80% aluminum. On a national basis, in 1996, U.S. secondary smelters consumed 1.44 million t of scrap with a calculated metallic recovery of 1.1 million t (Plunkert 1997a). This suggests that about 24% of the scrap charge is lost as aluminum and aluminum oxide in the dross.

### **Dust Production**

Based on the information in Section B.4.2, six pounds of baghouse dust are generated for each ton of scrap melted. In metric units, this corresponds to 3 kg per t, for a ratio of 0.3%. Some Pb and Cd may partition to the baghouse dust. Dust could be buried in a municipal landfill or on site.

### **Material Balance**

The following simplified material balance was developed for a typical secondary aluminum smelter using reverberatory furnaces to produce casting alloys based on 1,000 kg of metal charged into the furnace:

#### Furnace Charge:

- Aluminum scrap . . . . . 980 kg
- Silicon . . . . . 20 kg
- Flux . . . . . 60 kg

#### Output:<sup>9</sup>

- Aluminum casting alloy . . . . 943 kg
- Baghouse dust . . . . . 3 kg, containing 2 kg of metal

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<sup>9</sup> The output is greater than the furnace charge due to pick up of oxygen in the dross products.

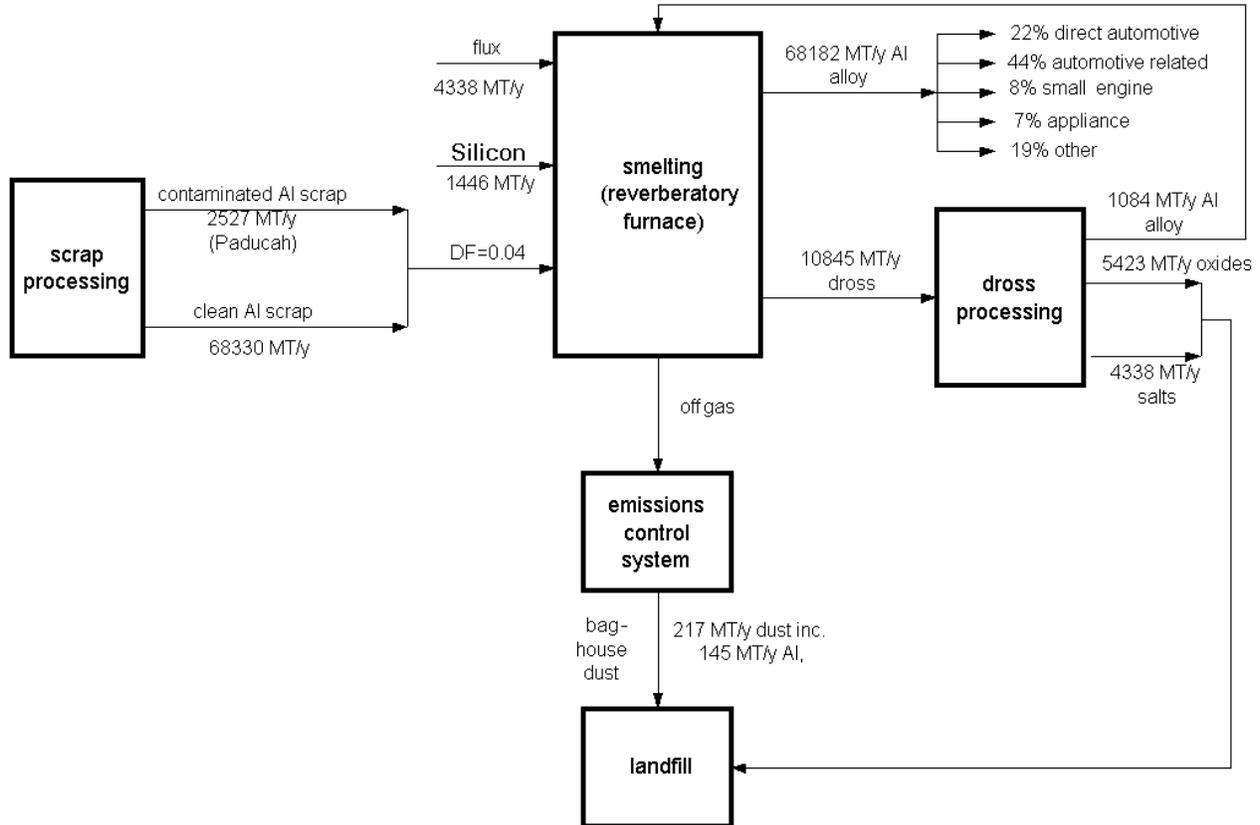


Figure B-6. Simplified Material Balance for Secondary Aluminum Smelter

- Dross ..... 150 kg, containing 60 kg of salts, 15 kg of Al, and 75 kg of oxide

This simplified material balance, which is illustrated in Figure B-6, ignores the minor effects of  $\text{Cl}_2$  injection and Mg removal. The material flows in Figure B-6 are for a full year.

Karvelas et al. (1991) quoted processing results from secondary aluminum smelters in the United States in 1988. For each 1,100 tons of aluminum produced, 114 tons of black dross and 10 tons of baghouse dust were generated. The composition of the black dross was 12% - 20% Al, 20% - 25% NaCl, 20% - 25% KCl, 20% - 50% aluminum oxide, and 2% - 5% other compounds. That study yields results similar to the simplified material balance proposed here. Karvelas et al. reported that 17 tons of aluminum were recovered from every 114 tons of black dross in 1988.

## B.6.2 Workers in the Secondary Aluminum Industry

### **Scrap Metal Transporter**

If the 2,527 t of scrap to be generated at Paducah were transported by a truck with 22-ton (20-t) capacity to a secondary smelter 170 miles (~275 km) away, it would take 126 trips. A driver would be exposed to the residually radioactive scrap for about four hours during each trip. However, since haulage costs are not the deciding factor in selecting the recycling facility, it is plausible for the scrap to be transported a greater distance, in which case a single driver could be occupied full time, hauling the scrap one-half the time and returning with an empty truck (or hauling other cargo).

### **Scrap Handler**

An operator is assumed to spend eight hours per day moving scrap from the stockpiles to the shredder or the furnace using a front-end loader with a five cubic yard bucket (the bucket would be loaded 50% of the time). In addition to exposure from the load being transported, he would receive additional external radiation exposure from the scrap piles and internal doses from dust inhalation or ingestion. The scrap is stored in piles and stacked bales of shredded metal. Assuming that the desired inventory level is 15 days' supply, a facility with an annual capacity of 68,000 t would typically have at least 3,000 t of inventory on hand. The actual inventory might be larger to accommodate special purchasing situations or seasonal needs.

### **Shredder Operator**

A typical shredder operator is assumed to spend seven hours per day running a scrap shredder (Figure B-3). The operator is assumed to stand beside the scrap conveyor which transports a stream of scrap 3 ft wide by 0.5 ft deep, with a 50% bulk density. Less than half the scrap is shredded.

### **Furnace Operator**

The furnace operator is assumed to do a variety of jobs in close proximity to the furnace. For example, he skims dross from the melt surface in the charging well using a mechanized skimmer on an extendable arm located at one side of the well. The operator sits in a booth on the skimming machine about 6 ft from the melt and transfers the dross to a container in front of the charging well. During the course of a week the operator spends 15 hours skimming dross, and 25 hours feeding alloying or fluxing agents into the furnace or performing other furnace-related work. Other work might include manually raking the furnace to remove bulk steel objects which

settle to the bottom. This is done twice per shift and requires 30 to 45 minutes per event (Kiefer et al. 1995).

### **Ingot Stacker**

Once the ingots are removed from the molds, they may require stacking onto pallets. According to Kiefer et al. (1995), this labor-intensive job requires a crew of four—two stackers and two forklift operators. The stackers pick up ingots from a rotary table and place them on a stacking pallet. It requires about 20 minutes for each stacker to load a 2,000-lb pallet. The forklift operators transport the pallets to a storage area. The stackers and the forklift operators trade jobs frequently during a shift.

### **Dross Hauler**

Dross containing 10% Al (with Co, Fe, Mn and Tc) and 90% salts and oxides (including elements such as U, Pu, Np and Cs ) might be shipped 400 miles (~645 km) by truck with a 20-ton (18-t) capacity. Approximately 11,000 t of dross—about 600 truck-loads—is produced each year at the reference facility described in Figure B-6 . A one-way trip would take over eight hours; therefore, transporting the dross would be a full-time occupation for four or five drivers.

### **Aluminum Fabricator**

Plasma arc cutting (PAC), gas metal arc welding (GMAW), and gas tungsten arc welding (GTAW) are processes typically used in fabrication of aluminum structures. An extensive study has been made of the metal fume levels associated with these processes (Grimm and Milito 1991). Tests were conducted using an instrumented mannequin in a special room where the air flow did not exceed 15 ft/min (~ 5 m/min or 7.6 cm/s). The mannequin was instrumented to measure fume concentrations inside and outside a welding helmet. Both a wrought base metal (2090) and a cast base metal (A356) were tested with different weld filler metals (1100, 2319, and 4043). Fume measurements are summarized in Tables B-16 and B-17 and indicate that the maximum fume level observed inside the welder's helmet was 7.66 mg/m<sup>3</sup>, associated with gas metal arc welding of alloy 2090. It is expected that the welder would be exposed to these fume levels no more than 50% of the time, with the balance of the workday involving setup, workpiece handling, and other operations.

### B.6.3 Users of End-Products

#### **Automobiles**

The average amount of aluminum used in North American cars and light trucks is 250 pounds, 65% of which is recycled metal (IMCO 1997, Lichter 1996). The aluminum content in luxury and specialty cars is higher—for example, the Plymouth Prowler uses 963 lb of aluminum (Drucker Research Company 1998). The use of aluminum in cars is a fast-growing market, having increased 35% over the last five years. If this trend is sustained for another five years, the average recycled aluminum content can be estimated to be 220 pounds ( $250 \times 1.35 \times 0.65$ ). Most of the recycled aluminum would likely be associated with under-the-hood components. Another author estimated that by 2010 domestic vehicles would use 283 pounds of aluminum castings (“Automotive Aluminum Recycling” 1994).

A recent study by the Drucker Research Company estimated that in 1999, the total aluminum content of passenger cars and light trucks will be 3.815 billion pounds based on 15.362 million units of production (Drucker Research Company 1998). Secondary aluminum made from old and new scrap will account for 63% of the 3.8 billion pounds (primarily as die and permanent mold castings). The total aluminum content per vehicle will average 248 pounds (of which 156 pounds will be secondary aluminum).

The largest single component is most likely the engine block. The approximate weight of a four-cylinder block is 40 lb (18 kg), a V-6 block weighs 55 lb (25 kg), while a V-8 ranges from 60 to 80 lb (27 to 36 kg) (Klimish 2001).

#### **Home Appliances**

Sources of exposure include ingestion of food cooked in cast aluminum frying pans<sup>10</sup> and external exposure to cast aluminum components in appliances. Aluminum usage in typical home appliances is as follows (Aluminum Association 1985):

- room air conditioners . . . . . 10 lb
- ranges . . . . . 2 lb
- refrigerators . . . . . 10 lb

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<sup>10</sup> Kitchen cookware is commonly made from wrought aluminum alloys such as 6061 rather than cast alloys. Some cast aluminum (e.g., 383 alloy) might be used for skillets (Graham 1997).

- dishwashers ..... 2 lb
- washers ..... 15 lb
- dryers ..... 4 lb

**Truck**

The tractor of a large truck can contain about 700 lb of aluminum in the cab shell (including the sleeper compartment) and under the hood. On a long haul the driver is limited by Department of Transportation regulations to a maximum of 15 hours per day of driving and on-duty time, including a maximum of ten hours of driving. The driver is also limited to 60 hours of on-duty plus driving time in a seven-day period. On-duty time includes such actions as loading and unloading the vehicle. In addition, the driver may spend time resting in the sleeper compartment. However, the cab is made from a large number of aluminum parts and the likelihood of all the parts coming from the same heat of aluminum is nil. The largest aluminum component that is made from one or two pieces of aluminum mill products is assumed to be a 100-gallon fuel tank that is mounted on the left side of the cab behind and below the driver.<sup>11</sup> If such a tank were fabricated from  $\frac{5}{16}$ -inch aluminum sheet, it would weigh about 180 lb.

**Motor Home**

The floor of an aluminum motor home contains about 600 lb of aluminum. As is the case with the truck cab, the motor home will be constructed from a variety of shapes, making it unlikely that all the material would come from a single heat.

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<sup>11</sup> The Freightliner C112 Tractor with 58-inch raised roof sleeper cab is configured in this way. According to a Freightliner spokesman, tanks weigh about 200 pounds.

Table B-16. Concentrations in Ambient Air Inside and Outside the Welder's Helmet During Aluminum Welding and Cutting

Component	Units	GMAW <sup>a</sup> 2090/2319		GMAW 2090/1100		GTAW <sup>b</sup> 2090/2319		GMAWA 356/4043		GMAWA 356/4043		GMAWA 356/4043		
		Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside	
NO	ppm	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	
NO <sub>2</sub>		<0.01	<0.02	<0.01	0.03	<0.01	<0.01	<0.01	0.23	<0.01	<0.01	<0.01	<0.01	
O <sub>3</sub>		0.16	0.22	0.09	0.14	<0.01	0.08	0.28	5.75	0.16	0.68	0.06	0.18	
Total fume	mg/m <sup>3</sup>	7.66	42.9	5.76	27.4	0.20	0.57	1.14	14.5	0.73	4.96	0.78	2.82	
Al <sub>2</sub> O <sub>3</sub>		7.12	40.60	5.71	25.97	0.05	0.23	0.96	13.97	0.70	3.48	0.36	1.59	
SiO <sub>2</sub>		—	—	—	—	—	—	0.12	0.99	—	—	—	—	
Fe <sub>2</sub> O <sub>3</sub>		—	0.07	0.131	0.05	—	—	—	—	0.04	0.04	—	—	
CuO		0.15	1.09	0.05	0.05	—	—	0.03	0.03	—	0.03	—	—	
Cr <sub>2</sub> O <sub>3</sub>		—	—	0.04	—	—	—	0.03	—	—	—	—	—	
MgO		—	<0.03	—	—	—	—	—	—	—	—	—	—	
MnO		—	0.07	—	—	—	—	—	—	—	—	—	—	
NiO		—	—	—	—	—	—	—	—	—	—	—	—	
TiO <sub>2</sub>		—	0.07	—	—	—	—	—	—	—	—	—	—	
ZrO <sub>2</sub>		—	—	—	—	—	—	—	—	—	—	—	—	
Li <sub>2</sub> O		—	0.06	—	—	—	—	—	—	—	—	—	—	
Sb		—	—	—	—	—	—	—	—	—	—	—	—	
BeO		μg/m <sup>3</sup>	—	—	—	—	—	—	<2.91	28.40	<1.87	<3.30	<2.14	<1.87
Be			—	—	—	—	—	—	—	<1.04	10.22	<0.67	<1.22	<0.77
Total oxides	mg/m <sup>3</sup>	7.29	42.00	6.04	26.08	0.06	0.23	1.10	15.05	0.75	3.52	0.36	1.60	
Oxide ÷ total fume	%	94.9	98.6	106.2	95.6	30.0	NV	92.1	104	122	73.6	53.7	68.9	

Note: — indicates analyses completed, but values do not exceed lower limit of detection (LOD). (For SiO<sub>2</sub>, LOD=0.03 mg/m<sup>3</sup>, for all other oxides, except BeO, LOD=0.02 mg/m<sup>3</sup>).

<sup>a</sup> Gas Metal Arc Welding

<sup>b</sup> Gas Tungsten Arc Welding

Table B-17. Dust Levels During Plasma Arc Cutting of Wrought Metal 2090 (mg/m<sup>3</sup>)

Component	Inside Helmet	Outside Helmet
Total fume	3.40	3.28
Al <sub>2</sub> O <sub>3</sub>	2.65	2.25
SiO <sub>2</sub>	—	—
Fe <sub>2</sub> O <sub>3</sub>	—	—
CuO	<0.03	—
Cr <sub>2</sub> O <sub>3</sub>	—	—
MgO	—	—
MnO	—	—
NiO	—	—
TiO <sub>2</sub>	—	—
ZrO <sub>2</sub>	—	—
Li <sub>2</sub> O	0.16	.14
BeO (µg/m <sup>3</sup> )	<1.40	<1.40
Be (µg/m <sup>3</sup> )	0.50	<0.50
Total oxides (mg/m <sup>3</sup> )	2.83	2.39
Total oxide/total fume (%)	71.4	66.5

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**APPENDIX B-1**

**DESCRIPTION OF SELECTED SECONDARY SMELTERS**

Table B1-1. Description of Selected Secondary Smelters

Facility	Bag House Type	Dust Disposal	Pretreatment	Dross Handling	Radiation Detectors	Furnaces
Ohio Valley Aluminum, Shelbyville KY	None	N/A	None	Skimmed into containers and sold	Not used	Three, 9.5 million lb/mo total
Rock Creek Aluminum, Rock Creek OH	??	??	Crushing and screening	N/A	Hand-held Geiger counter	60 million/y, no melting
Alcan Recycling, Shelbyville TN	On shredder, decoater, and furnaces. Furnace bags coated w/ Ca(OH) <sub>2</sub>	BFI ships to secured landfill	Shredding and decoating	Sold to Tennessee Processors, Al repurchased	Fixed Ludlum detectors	Two reverberatory, 40 to 50,000 tons/y total
Sceptar Industries, New Johnsonville TN	On rotary furnaces but not on reverberatories	To on-site landfill	Very little pre-processing	Dross is remelted	Not used	Two reverberatory, three rotary 12-14 million lb/month
IMCO Recycling, Morgantown KY	Lime-coated bags. One ton of dust per 100 tons of feed.	Both on-site & off-site landfills used. On-site equivalent to Sub-Title C, although not required	Shredder			Rotary furnaces: reverberatory under construction, 220 million lb/y current capacity
IMCO Recycling, Uhrichville OH		Off-site				360 million lb/y
U.S. Reduction, Toledo OH	Unknown	Off-site	Large and small crusher and dryer	Shipped to independent process	Not used	Two reverberatory
Wabash Alloys, Dixon TN	Lime-coated bags	BFI to municipal landfill	Shredder	Shipped to company plant in Benton, Ark.	Fixed	Four reverberatory, 220,000 lb each, 150 million lb/y total.

B1-1

**APPENDIX B-2**

**SECONDARY ALUMINUM SMELTER OPERATIONS AT  
ARKANSAS ALUMINUM ALLOYS INC.**

## **SECONDARY ALUMINUM SMELTER OPERATIONS AT ARKANSAS ALUMINUM ALLOYS INC.<sup>12</sup>**

### **B2.1 FACILITY DESCRIPTION**

Arkansas Aluminum Alloys, Inc. (AAAI) is an aluminum recycling facility (secondary aluminum smelter) that has been in business since 1974. AAAI produces aluminum stock with varied elemental composition depending on customer specifications. Approximately 165 employees (administration and production) work at the facility. The facility operates 24 hours per day, 355 days per year, with four rotating work shifts. Employees receive two 10-minute breaks and a 30-minute lunch period per shift. There are three gas-fired reverberatory furnaces at the smelter. However, except for times of extreme production demands, only two furnaces are operated at one time. Office, warehouse, and production space occupies 57,130 square feet, situated on nineteen acres. Smoking is permitted in the manufacturing areas.

### **B2.2 PROCESS DESCRIPTION**

AAAI receives and processes all types of reclaimable aluminum scrap except cans. Most (98%) of the scrap aluminum is delivered by tractor-trailer truck, weighed, scanned for radioactivity, unloaded, and spread in the storage area. The scrap is then placed on a conveyor where it is visually inspected and manually sorted. Iron, stainless steel, zinc, brass, and other materials are removed at this station. The scrap is then sampled and analyzed and placed in storage bins based on elemental composition. AAAI has an on-site laboratory with a sophisticated elemental analyzer that requires very little sample preparation and provides rapid results. Some of the sorted scrap is shredded and crushed and screened to removed dirt. A magnet is used to separate iron from the aluminum. The shredded scrap is then placed in bins. A gas-fired kiln located at the back of the facility is used to dry machined turnings prior to processing in the melting furnace.

There are three 220,000-lb capacity gas-fired furnaces at AAAI. Each furnace is equipped with exhaust ventilation to control flue gas, as well as fume control (canopy hoods). Fume exhaust is conveyed to a roof-mounted baghouse system. Furnace runs last approximately 20 hours, followed by a 4½ hour pour time. The pour temperature of the melt is approximately 1380°F.

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<sup>12</sup> Source: Keifer et al. 1995

About 80,000 lb of molten aluminum are left in the furnace to prime the next run. To charge the furnace, the furnace operator will open large overhead doors on one side of the furnace and use a front-end loader to place the scrap into wells adjacent to the furnace. After charging, the overhead doors are closed, and the scrap melts and flows into the main furnace body. Samples are periodically taken from the melt with a ladle and analyzed to ensure that the final product meets customer specifications (elements are added if necessary to meet customer requirements). Copper and silicon are the major elements added; this is done by placing into a hopper at the front of the furnace. The majority (over 95%) of AAAI customers purchase the finished aluminum in 30-lb ingots. AAAI will also accommodate those few customers who request 1000-lb aluminum “sows.”

Magnesium is a common contaminant that must be scavenged (by demagging) from the melt to reduce the concentration below 0.1%. At AAAI, this is accomplished by injecting chlorine gas into the melt—piped from a 55-ton tank car, through vaporizers, to each furnace—via a graphite pump and carbon tubes. The chlorine combines with the magnesium to form  $MgCl_2$ , which is then skimmed off the top of the melt. If necessary,  $AlF_3$  can be used instead of chlorine for this “demagging” operation. According to AAAI,  $AlF_3$  is rarely used. Salt (NaCl), potash, and cryolite are added to every charge as a flux to remove dirt and prevent oxidation of the melt.

Iron is considered a major detriment to the product, and every attempt is made to eliminate it during initial inspection and by the use of magnetic separation prior to processing. However, some iron inevitably gets into the furnace, sinks to the bottom, and must be manually removed. Periodically (twice per shift), furnace operators manually drag a large rake along the bottom of the melt to pull the iron out of the furnace. Each raking event takes about 30 to 45 minutes.

During pouring, the furnaces drain into an insulated open trough. To start the pour, a furnace plug is removed and the molten metal flows continuously through the trough into 1½ ft long, 30-lb molds (or 100-pound molds if necessary). The 30-lb molds are on a carousel/conveyor system and pouring occurs as the molds move sequentially through a water bath. This area is shielded because of the potential for violent reactions in the event molten aluminum contacts the water. After the molds have passed through the water, two workers stand adjacent to the conveyor line and skim dross from the ingots using hoe-like hand tools. The ingot molds are then elevated on the carousel and rotated to release the ingots onto a conveyor belt. Graphite is used as a mold-release agent. An automated pneumatic hammer is used to remove the ingots from the molds if necessary.

The ingots are then conveyed to the stacking area where they are dropped onto a rotating table. The surface temperature of the ingots is approximately 230°F when received at the stacking station. Stacking is a 3- or 4-man labor-intensive operation (2 stackers, 2 forklift operators), and workers continuously rotate between stacking and forklift operation. As the ingots are deposited onto the table, the stacker will pick up the ingot and place it in position on a stacking pallet. Stackers are also required to inspect the ingots and recycle those found to be defective. Each stacker will load one 2000-lb stack (approximately 18-20 minutes), and then switch jobs with the forklift operator. The fully stacked pallets are then moved to a cooling room, and finally to the warehouse. AAI has a fleet of trucks for shipping product to customers.

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**APPENDIX C**  
**COPPER RECYCLING**

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## COPPER RECYCLING

This appendix presents background material to support an analysis of exposures expected from the recycling of copper scrap.

### C.1 INVENTORY OF POTENTIALLY RECYCLABLE COPPER SCRAP

#### C.1.1 Scrap Metal Inventory

The Scrap Metal and Equipment Appendix to the 1996 MIN Report (U.S. DOE 1995) identified 1,691 metric tons<sup>1</sup> (t) of copper and brass scrap in inventory. This inventory was classified as containing 1,490 t of contaminated metal, 53 t of clean scrap metal, and 148 t of material unspecified as to its state of contamination. (These amounts are slightly higher than the inventory listed in Table 4-4 of the present report)<sup>2</sup>. A detailed breakdown by location is provided in Table C-1. Based on the ratio of clean to contaminated scrap, 143 t of the unspecified material was categorized in the present study as contaminated, resulting in a total of 1,633 t of potentially contaminated 58 t of clean copper and brass scrap. As discussed in Section 4.1.4, the HAZWRAP Report (Parsons 1995) listed inventories of contaminated scrap metal at LANL and Rocky Flats which were omitted from the MIN Report. It is therefore likely that some unreported copper scrap may be in inventory at these two sites.

Obviously, most of the current inventory is at Fernald. DOE has entered into an arrangement with Decon and Recovery Services LLC (DRS) of Oak Ridge, Tenn. to process about 1,200 t of copper scrap (primarily motor windings) from Fernald (Deacon 1999). DRS will mechanically remove the insulation, which is slightly contaminated, leaving behind clean copper that, in the future, could be released for unrestricted sale under the provisions of DOE Order 5400.5.<sup>3</sup>

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<sup>1</sup> This appendix includes numerous references with widely varying units of measurement. The authors of this appendix have generally chosen not to convert the units to a consistent system but rather have chosen to quote information from the various sources in the original units. When the cited information is distilled into scenarios for modeling doses and risks, consistent units are used.

<sup>2</sup> These data are slightly higher than those in Summary Table 1.4 of U.S. DOE 1995 because that table did not include all individual sites.

<sup>3</sup> As noted in Chapter 2, DOE currently has a moratorium on the free release of volumetrically contaminated metals and has suspended the unrestricted release for recycling of scrap metal from radiological areas within DOE facilities.

Table C-1. Current Inventory of Copper Scrap at DOE Facilities (t)

Location	Clean	Contaminated	Unspecified
Fernald		1270	
ANL-W	6.3		
Hanford	33		
BNL		200	
FermiLab		9.2	
SRS	2.5	11	
WIPP	0.23		
NTS	0.90		
SLAC	4.8		
LBL	4.8		
K-25			42
Y-12			44
ORNL			1.8
Portsmouth			21
Paducah			39
Total	53	1490	148

The principal future sources of DOE copper scrap are the gaseous diffusion plants at Oak Ridge; Paducah, Ky., and Portsmouth, Ohio. It has been estimated that these plants contain 40,200 t of copper scrap (National Research Council 1996)<sup>4</sup> with individual facility totals as follows:

- K-25 ..... 16,000 t
- Portsmouth ..... 13,600 t
- Paducah ..... 10,600 t

The copper is present in the form of wire, tubing, and valves, with the following breakdown reported for the K-25 plant (U.S. DOE 1993):

---

<sup>4</sup> These values were derived from a 1991 study by Ebasco Services, Inc., which estimated that the total radioactive scrap metal arising from decommissioning the three gaseous diffusion plants would be 642,000 t. This estimate did not include carbon steel in the building structures but did include electrical/instrumentation equipment and housings. Person et al. (1995) estimated that 1,047,000 t of scrap metal would be recycled including structural steel. Of this total, 60.3% is estimated to be potentially contaminated and the balance to be clean. Thus, these authors predicted the same total amount of radioactive scrap metal as the earlier Ebasco study; they did not provide a breakdown by metal type.

- copper tubing/valves . . . . . 0.19 t
- large copper wire . . . . . 8.6 t
- small copper wire . . . . . 7.2 t

The three plants contain an additional 20,200 t of "aluminum/copper," but the two metals are not separated by type. The above estimates do not include any copper in "miscellaneous electrical/instrumentation and housings" (U.S. DOE 1993). No information is available on copper scrap expected to be generated at other DOE facilities.

To develop a recycling schedule for DOE facilities, the procedure described below was used. Existing scrap is assumed to be available for processing in 2003. The existing inventory is adjusted to remove the Fernald motor windings, since this scrap is being handled currently. The decommissioning schedule for the three diffusion plants is as follows (see Section 4.1.5):

- K-25 . . . . . 1998-2006
- Portsmouth . . . . . 2007-2015
- Paducah . . . . . 2015-2023

It is assumed that no scrap is generated in the first year of a nine-year decommissioning period, 13% is generated in years 2 through 8, and 9% in the final year. Scrap generation based on this schedule is summarized in Table C-2.

Table A-29 lists the amounts of copper, brass, and bronze used to construct a 1971-vintage, 1,000 MWe PWR facility. Specific information is not available on the amount or contamination level of radioactively contaminated copper scrap that would be generated during the decommissioning of such a facility. Consequently, it is assumed that the contaminated fraction of copper scrap is the same as contaminated fraction of carbon steel from the Reference BWR and Reference PWR facilities.

Extending the data in Table A-29 to the entire U.S. commercial nuclear power industry leads to the conclusion that approximately 73,000 t of copper would be generated by the decommissioning of the facilities listed in Appendix A-1 . Only a small portion of this metal is expected to be contaminated. Some of the contaminated inventory may not be suitable for free release. Based on the results for carbon steel presented in Appendix A, it is assumed that 20% of the copper scrap from the Reference BWR would be residually radioactive metal that is potentially

recyclable, while 10% of the copper scrap from the Reference PWR would fall into this category. Applying these factors yields 9,691 t of potentially recyclable contaminated copper, as shown in Table 4-8. As shown in that table, the nuclear power plants also contain small quantities of brass and bronze. These copper alloys were not included in this analysis. Since the annual availability of these alloys should be less than 50 t in toto, sizable dilution with uncontaminated scrap is expected; thus, the omission of these metals should have no significant impact on the radiological assessment.

The schedule of anticipated releases of scrap metals from nuclear power plants is presented in Table 4-9. The data for copper are reproduced in Table C-2.

From Table C-2, it can be seen that the maximum projected annual amount of DOE and commercial nuclear power plant copper scrap to be available for clearance is 10,833 t in the year 2003. This includes the 1,633-t inventory derived from U.S. DOE 1995 (less 1,200 t of Fernald scrap assumed to have been removed to date), and a stockpile of copper scrap accumulated during five years (1999 - 2003) of decommissioning and dismantlement of the K-25 facility. This projection is based on the assumption that DOE will resume clearing scrap metal for recycle by 2003 (see Section B.1.1). The total of 50,300 t of potentially recyclable scrap in Table C-2 is in good agreement with a more recent DOE estimate of 51,000 t of radioactive copper scrap (Adams 1998).

### C.1.2 Radionuclide Inventory

As indicated in Section C.1.1, the majority of scrap copper will be generated from the gaseous diffusion plants. The naturally occurring uranium isotopes and their short-lived progenies are the principal source of contamination at the diffusion plants. Other contaminants include Tc-99, U-236, and traces of Pu-239 and Np-237. It has been estimated that the following activities were introduced into the Paducah gaseous diffusion plant, relative to 250 kCi of U-238 (National Research Council 1996):

- U-236 ..... 900 Ci
- Tc-99 ..... 11,200 Ci
- Np-237 ..... 13 Ci
- Pu-239 ..... 20 Ci
- Th-230 (+ progeny) ..... 140 Ci

• Pa-231 (+ progeny) ..... 16 Ci

Table C-2. Availability of Copper from Decommissioning of Nuclear Facilities (t)

Year	DOE Facilities	Commercial Nuclear Power Plants	Year	Commercial Nuclear Power Plants
2003	10,833	—	2027	207
2004	2,080	—	2028	247
2005	2,080	—	2030	215
2006	1,440	103	2031	285
2007	—	24	2032	673
2008	1,770	—	2033	425
2009	1,770	—	2034	711
2010	1,770	—	2035	564
2011	1,770	—	2036	954
2012	1,770	—	2037	374
2013	1,770	—	2038	129
2014	1,770	—	2039	286
2015	1,210	—	2040	77
2016	1,380	115	2043	201
2017	1,380	—	2044	124
2018	1,380	—	2045	75
2019	1,380	235	2046	62
2020	1,380	189	2047	19
2021	1,380	172	2049	62
2022	1,380	537	2052	38
2023	940	654	2056	69
2024	—	1,074	2057	69
2025	—	132	2058	98
2026	—	517		
Total	40,633			9,715

Much of this contamination was removed during the cascade upgrade and improvement programs of the 1980's (National Research Council 1996). The other significant source of copper scrap is Fernald. Beginning in 1953, the Feed Materials Production Center (now known as the Fernald Environmental Management Project [FEMP]) converted uranium ore to uranium metal

targets for nuclear weapons production. Over a 36-year period, this facility produced over 225,000 t of purified uranium. The principal radioactive contaminants include the uranium isotopes (and their short-lived progenies) and Tc-99.

In commercial nuclear power plants, activation of copper should be negligible. Naturally occurring copper consists of two isotopes: Cu-63 (69%) and Cu-65 (31%). In a nuclear power reactor, thermal neutrons create only small amounts of Cu-64 and Cu-66, because the neutron-capture cross-sections of the naturally-occurring copper isotopes are small. These radioisotopes, with respective half-lives of 12.7 hr and 5.1 min, undergo  $\beta$ -decay to the stable isotopes Zn-64 and Zn-66 in. Thus, the major source of radioactive contamination will be surface contamination caused by a broad suite of radionuclides (Epel 1997).

## C.2 RECYCLING OF COPPER SCRAP

Copper scrap can enter copper refining and processing operations in a variety of ways, depending on factors such as the quality of the scrap and its alloy content. For example, some copper scrap may be refined at primary copper smelters and some at secondary smelters. Copper alloy scrap may be remelted at brass mills, ingot makers, or foundries. This section characterizes the manner in which copper and copper alloy scrap are recycled.

### C.2.1 Types of Copper Scrap

The Institute of Scrap Recycling Industries (ISRI) and the National Association of Recycling Industries recognize various major classes of copper scrap (NARI 1980, Newell 1982, Riley et al. 1984). The major unalloyed scrap categories are termed No. 1 copper, which must contain more than 99% copper, and No. 2 copper, which must contain a minimum of 94% copper. For copper alloys, ISRI has identified 50 separate scrap classifications. Additional classifications exist for copper containing waste streams, such as skimmings, ashes and residues generated in copper smelting and refining processes.

Copper scrap is further categorized as either “old” or “new” scrap. New scrap is generated during fabrication of copper products. For example, copper-containing end-products that are manufactured from intermediates, such as copper sheet, strip, piping, or rod, may have product yields as low as 40%. These new scrap materials generated from borings, turnings, stampings, cuttings, and “off-specification” products are commonly sold back to the mills that produced the original intermediates from which the new scrap was generated. Since both new scrap and

manufactured scrap are recycled within the copper industry, neither is considered to be a new source of copper.

Old scrap, which is generated from worn-out, discarded, or obsolete copper products, does constitute a new (i.e., from outside the industry) source of metal for the secondary copper industry. Since World War II, the reservoir of copper products in use has increased dramatically, both in the U.S. and globally. The U.S. scrap inventory increased from 16.2 million tons in 1940 to nearly 70 million tons in 1991 (Bureau of Mines 1993). The availability of copper scrap is linked with the quantity of copper-containing products and their life-cycles. Estimates of life cycles have been made for major products: copper used in electrical plants and machinery averages about 30 years, in non-electrical machinery about 15 years, in housing 40 years or more, and in transportation about 10 years (Carlin et al. 1995).

Copper scrap may also be broadly categorized into four main types based on copper content and the manner in which it is treated for copper recovery (as quoted from Davenport 1986):

- Low-grade scrap of variable composition (10-95% Cu). This material is smelted in blast or hearth furnaces and then fire and electrolytically refined. It may also be treated in Peirce-Smith converters of primary smelters.
- Alloy scrap, the largest component of the scrap recovery system, consists mainly of brasses, bronzes, and cupronickels from new and old scrap. There is no advantage in re-refining these alloys to pure copper, and hence they are remelted in rotary, hearth, or induction furnaces and recast as alloy stock. Some refining is done by air oxidation to remove aluminum, silicon, and iron as slag, but the amount of oxidation must be closely controlled because desirable alloy constituents (Zn in brasses and Sn in bronzes) also tend to oxidize.
- Scrap, new or old, which is by and large pure copper but which is contaminated by other metals (e.g. metals used in plating, welding, or joining). This scrap, is melted in the Peirce-Smith converters of primary smelters or the anode furnaces of primary or secondary refineries, where large portions of the impurities (e.g. Al, Fe, Zn, Si, Sn) are removed by air oxidation. The metal is then cast into copper anodes and electro-refined .... It may also be sold as fire-refined copper for alloy making.
- Scrap which is of cathode quality and requires only melting and casting. This scrap originates mainly as wastes from manufacturing (e.g. reject rod, bare wire, molds). It is melted and cast as ingot copper or alloyed and cast as brasses or bronzes.

According to the U.S. Geological Survey, in 1997, about 496,000 t of copper were recovered from old scrap and 956,000 t from new scrap. This resulted in 1,450,000 t of copper consumption in the U.S. from scrap (Edelstein 1998). This quantity of copper was contained in 1,750,000 t of scrap metal. Table C-3 summarizes the kinds of scrap involved in copper recycle and the form in which the copper was recovered. It is important to note that alloy scrap will typically be reused in similar alloys. Aluminum scrap containing copper will be used in aluminum alloys; brass scrap will be used in brass, etc. However, pure recycled copper can conceptually be used either as pure copper or as an alloying agent.

In 1997, consumers of this scrap included about 35 brass mills, several brass and bronze ingot makers, 15 wire mills, four secondary smelters, seven primary smelters, six fire refineries, eight electrolytic plants, and 600 foundries, chemical plants, and miscellaneous consumers (USGS 1998). The quantities of old and new copper-base scrap used by these consumers are summarized in Table C-4. The total in this table is less than the total in Table C-3 because Table C-4 includes only copper-base but not other copper-containing scrap.

A simplified flow diagram for the copper scrap consumption documented in Table C-4 is included as Figure C-1. This figure illustrates the disposition of 1,370,000 t of copper in copper-base scrap. It is apparent from the diagram that the flow paths are numerous and complex. Information presented by Edelstein (1998) indicates that, of the 383,000 t of copper in scrap that is processed by smelters and refiners (i.e. the box on the left of Figure C-1), about 39% is No. 1 wire and heavy scrap. Although Figure C-1 indicates that scrap was processed by four secondary smelters in 1997, currently only two secondary smelters are operating (Chemetco in Hartford, Ill. and Southwire in Carrollton, Ga). Chemetco produces anodes, which are sent to another processor (Asarco) for electrolytic refining. Southwire does its own electrolytic refining.

### C.2.2 Scrap Handling and Preparation

Copper scrap is collected by a national network of processors and brokers. The scrap is visually inspected and graded. Chemical analyses are performed when necessary. Loose scrap is baled and stored until needed. Alloy scrap is segregated and identified by the alloy and the impurity content of each batch. Scrap of unknown composition may be melted and analyzed to determine its chemistry (CDA 1998a). The major processes involved in secondary copper recovery are scrap metal pretreatment and smelting. Pretreatment prepares the scrap copper for the smelting process. Smelting is a pyrometallurgical process used to separate, reduce, or refine the copper.

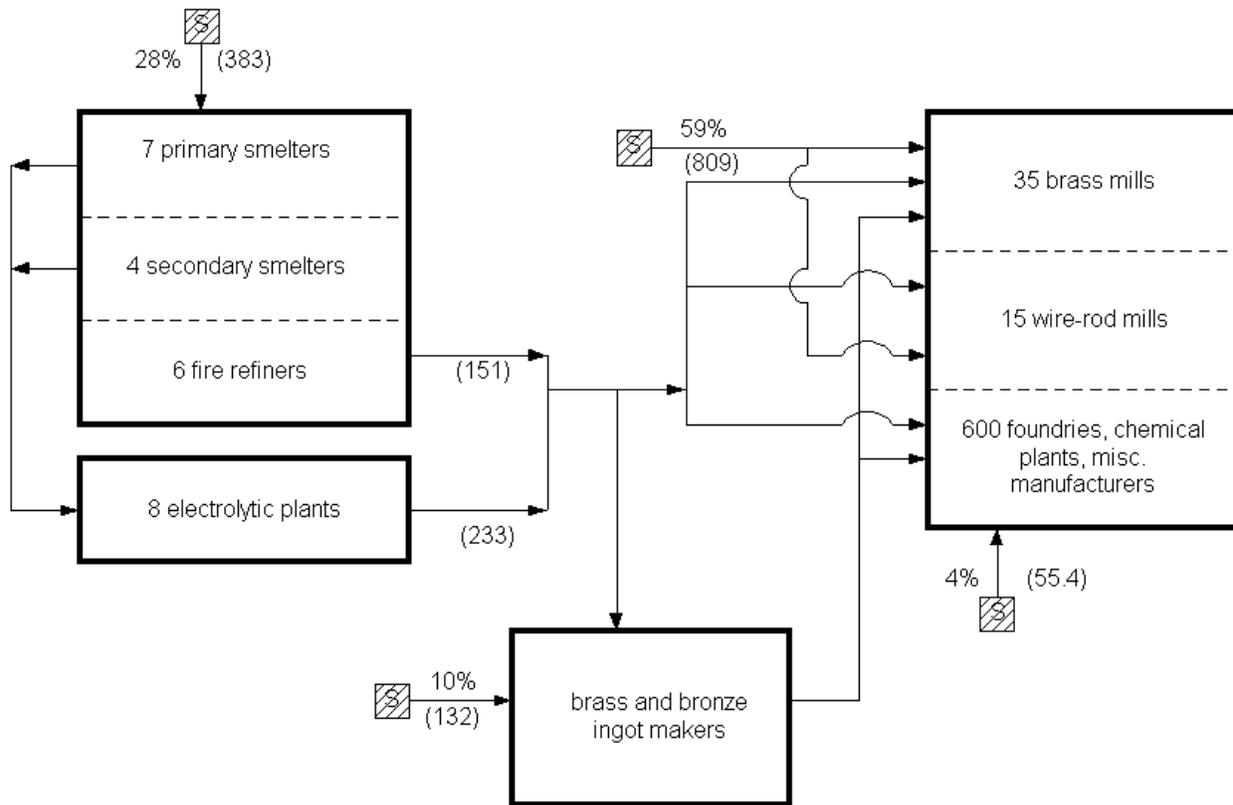


Figure C-1. Simplified flow diagram for copper-base scrap in 1997. Units are percent of total copper consumed from copper-base scrap and metric tons (in parentheses).

Pretreatment includes cleaning, and concentrating the scrap materials to prepare them for the smelting process. Pretreatment can be accomplished by: (1) concentration, (2) pyrometallurgical, or (3) hydrometallurgical methods. These methods may be used separately or combined. Pretreatment by concentration is performed either manually or mechanically by sorting, stripping, shredding, or magnetic separation. The resulting scrap metal is then sometimes briquetted in a hydraulic press. Pretreatment by the pyrometallurgical method includes sweating, burning of insulation (especially from scrap wire), and drying (burning off oil and volatiles) in rotary kilns. The hydrometallurgical method includes flotation and leaching with chemical recovery. After pretreatment the scrap metal is ready for smelting (U.S. EPA 1995).

Table C-3. Copper Recovered from Scrap Metal Processed in the United States in 1997

Scrap		Amount (t)	
Kind of Scrap	New Scrap	Copper-base	909,000
		Aluminum-base	46,800
		Nickel-base	91
		Zinc-base	—
		Total	955,891
	Old Scrap	Copper-base	465,000
		Aluminum-base	30,300
		Nickel-base	28
		Zinc-base	19
		Total	495,347
Grand total		1,451,238	
Form of Recovery	As unalloyed copper	At electrolytic plants	233,000
		At other plants	161,000
		Total	394,000
	As alloys and compounds	Brass and bronze	979,000
		Alloy iron and steel	743
		Aluminum alloys	77,500
		Other alloys	113
		Chemical compounds	252
		Total	1,057,608
	Grand total		1,451,608

Source: Edelstein 1998

Note: Totals differ due to round-off errors.

### C.2.3 Copper Refining Operations

Copper scrap is utilized by both primary and secondary producers of copper. Locations in the copper refining process where copper scrap may be introduced are summarized in Figure C-2. This diagram does not address the large amount of copper-alloy scrap, which is used by brass mills, ingot makers, and foundries. Based on the data in Table C-4, the figure illustrates the disposition of 63% of old scrap. In this figure, typical secondary copper operations are described by the dashed boxes.

Secondary smelters use several processes that are equivalent to those employed as primary pyrometallurgical processes for mined copper ores. A first stage smelting process is most commonly performed in either a blast furnace, reverberatory furnace, or an electric furnace. This is followed by treatment in a converter furnace and then in an anode furnace. The copper may be further purified by electrolytic refining. Depending on the grade, copper scrap may enter the flow stream at numerous locations. Some slag from the process is sold or landfilled; the remaining slag is recycled back into the smelting furnace because of its copper content. Sulfur dioxide, a by-product gas from *primary smelting*, can be collected, purified, and made into sulfuric acid for sale or for use in hydro-metallurgical leaching operations. Each of the major processes used in recycling copper scrap is described below.

Table C-4. Copper Consumption from Copper-Base Scrap in the United States in 1997 (t)

Type of Operation	From New Scrap	From Old Scrap	Total
Brass/bronze ingot makers	35,200	96,500	132,000
Copper refineries	91,400	292,000	383,000
Brass and wire-rod mills	771,000	32,800	804,000
Foundries and manufacturers	11,200	43,900	55,100
Chemical plants	252	—	252
Total	909,052	465,200	1,374,352

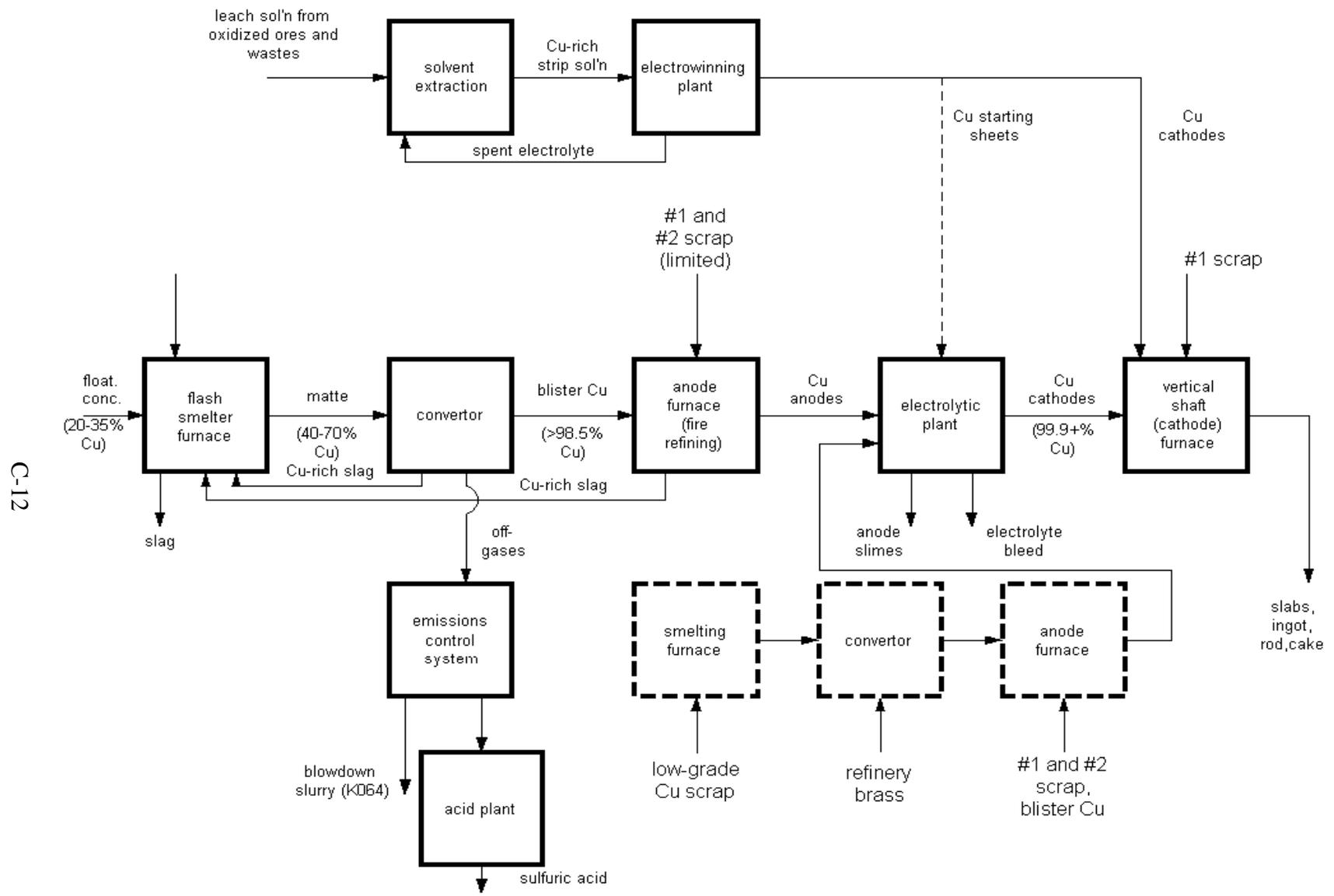
Note: Totals differ due to round-off errors.

### C.2.3.1 Copper Smelting Practices

#### **Blast Furnace**

The vertical shaft furnace, also known as the blast furnace or cupola, has the ability to smelt copper-bearing material of an extremely diverse physical and chemical nature. It is the unit that is commonly employed in the pyrometallurgical treatment of low-grade secondary copper material and largely controls the metal losses in the system (Nelmes 1984).

Low-grade copper scrap containing skimming, grindings, ashes, iron-containing brasses, and copper residues is typically smelted in a blast furnace, where coke is added as a reductant and limestone is added to assist in forming a calcium-iron-silicate slag. The molten “black copper” product from the blast furnace is transferred via a ladle to a converter for further purification. It is then fire refined and electrorefined. Dusts from the blast furnace are collected in a baghouse.



C-12

Figure C-2. Process diagram for the flow of copper scrap in primary and secondary copper refining. (Dashed boxes represent secondary processor's operations.)

The ranges of compositions for blast furnace process streams, as reported by several authors, are summarized in Table C-5. The feed to the cupola described by Opie et al. (1985) contained about 30% copper. The average dust composition from a cupola has also been reported by Garbay and Chapuis (1991):

- Cl ..... 3%
- Cu ..... 4%
- Zn (ZnO) ..... 55%
- Sn ..... 4%
- Pb ..... 9%

The dust composition, which is typical of French smelting practice, is encompassed by the ranges of values in Table C-5.

Table C-5. Composition of Process Streams from the Smelting of Copper Scrap in a Cupola Blast Furnace (%)

Item	Black Copper			Slag		Dust		
	Kusik and Kenahan	Nelmes	Opie	Nelmes	Opie	Kusik and Kenahan	Nelmes	Opie
Cu	75 - 88	80	65 - 70	0.9	1.5 - 2	0.1	1.5	8 - 12
Ni		4	7.5 - 12	1.5	1 - 1.5			0.1 - 0.5
Sb	0.1 - 1.7		0.5 - 1.5		1 - 2	0.1		0.3 - 0.8
Sn	1.5	4	2 - 4	0.3	1 - 2	5 - 15	1	1.5 - 2
Fe	3 - 7	5	5 - 10	30	30 - 35			
Zn	4 - 10	3	2 - 4	3	2 - 4	58 - 61	50	20 - 35
Pb	1.5	4	2 - 4	0.6	1.5 - 3	2 - 8	15	13 - 15
SiO <sub>2</sub>				27				4 - 7
Cl						0.1 - 0.5		6 - 10
F								1 - 5
CaO				14				
Al <sub>2</sub> O <sub>3</sub>				9				
Other		<1		15			32.5	

Sources: Kusik and Kenahan 1978, Nelmes 1984, and Opie et al. 1985.

During the blast furnace smelting operation, the scrap charge is fed onto a belt conveyer, which in turn discharges into one of two skip hoist buckets (Browne 1990). These buckets are hoisted and alternately dumped into opposite sides of the furnace. Coke is added as a reducing agent along with silica, lime, or iron oxide. Air is injected by means of tuyeres. The copper-bearing material initially enters at the top of the furnace into a zone at 400-600°C. It subsequently descends into the tuyere zone and increases in temperature to about 1,400°C<sup>5</sup> (Schwab 1990). According to Nelmes (1984), many secondary copper blast furnaces have an area of about 35 ft<sup>2</sup> with the range being from 12 to 140 ft<sup>2</sup>. Assuming a melting rate of 6 tons/ft<sup>2</sup>/day, a typical blast furnace would have an output of 210 tons/day.

A mixture of molten copper and slag flows down a launder into an oil-fired rocking furnace that can rotate. This furnace is large enough to give the slag sufficient time to separate from the copper. Rotating the furnace in one direction allows the liquid copper to fill a preheated ladle on a rail car below the rocking furnace. Rotation in the opposite direction allows the slag to pour into a granulating trough. Granulation is accomplished by impinging the liquid slag with a high pressure jet of water. The slag and water are collected in a pit that is large enough to remove the slag with a clamshell bucket on a crane.

When granulated blast furnace slag is dried, crushed, and screened, it is used to manufacture a variety of commercial products. It is useful for making a variety of abrasives, filler for asphalt shingles, roofing sealers, grit for sand blasting, road surface bedding, and in the manufacturing of mineral wool and light-weight cement aggregates (Nelmes 1984, Schwab 1990, Mackey 1993). The metal content of the slag is typically 1% copper or less (Mackey 1993). Some slag is stored or discarded in piles on site (U.S. EPA 1995).

In some cases the slag may be treated for recovery of additional metal values prior to granulation. Opie et al. (1985) describe a processing step in which the blast furnace slag is pyrometallurgically treated in an electric arc furnace with 2% coke added as a reductant. The arc furnace temperature is 100 to 200°C higher than in the blast furnace. A small amount of additional black copper is produced, dust is collected in a separate baghouse, and a slag with reduced metal values is obtained. The composition ranges for these products are presented in Table C-6 and are based on treating the blast furnace slag described by Opie et al. (1985) (see Table C-5).

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<sup>5</sup> The melting point of pure copper is 1,083°C.

Table C-6.  
Composition of Products Obtained from Treating Copper Blast Furnace Slag in an EAF

Element	Black Cu (%)	Final Slag (%)	Baghouse Dust (%)
Cu	55 - 60	0.2 - 0.5	1 - 2
Ni	5 - 10	0.2 - 0.4	0.2 - 0.3
Sb	0.5 - 1.5	0.1 - 0.20	0.1 - 0.2
Sn	2 - 4	0.05 - 0.1	1.5 - 3.0
Fe	5 - 7	30 - 35	0.5 - 0.7
Zn	1.5 - 2.0	0.5 - 1.0	45 - 55
Pb	1.0 - 1.5	0.5 - 1.0	15 - 20

Source: Opie et al. 1985

For a 100-ton blast furnace charge consisting of copper scrap, coke, and slagging agents, the expected output is 40 tons of black copper, 40 tons of slag, and 5 tons of baghouse dust (Nelmes 1984). Carbon in the charge is converted to CO/CO<sub>2</sub>, which is exhausted through a stack. The overall elemental partitioning for a copper blast furnace, based on these mass partitioning values and the elemental compositions included in Table C-5, is presented in Table C-7.

Table C-7. Partitioning During Blast Furnace Smelting of Copper Scrap (% recovery)

Output	Cu	Sn	Fe	Zn	Pb	Ni	Al <sub>2</sub> O <sub>3</sub>	CaO	SiO <sub>2</sub>
Metal	98.64	90.4	14.29	24.49	61.78	63.9	--	--	--
Dust	0.25	2.82	--	51.02	28.96	--	--	--	--
Slag	1.11	6.78	85.71	24.49	9.26	36.1	100	100	100

Source: Nelmes 1984

Table C-7 does not include 1.6 tons of “Other” material reporting to the dust and 6.0 tons reporting to the slag.

### Reverberatory Furnace

Reverberatory furnace smelting began in the nineteenth century. It still accounts for a significant fraction of both primary and secondary copper production and recycling of secondary scrap metal. Disadvantages of these furnaces are the long melting cycle times and low fuel efficiencies (Davenport 1986).

In a reverberatory furnace, the scrap copper is charged into one or more piles located behind one another, in front of several high capacity end-wall-fired burners. These high capacity conventional burners typically are fired above the copper scrap and use the reverberatory effect for heat transfer, i.e., re-radiation from the refractory roof and walls to the scrap. During the melting cycle, when the process requirements for energy are high, the surface of scrap exposed to the flame radiation and to radiative heat transfer from the furnace refractory surfaces is small relative to the total surface area of the scrap. This is because the top layers of scrap shade the interior scrap surfaces from the radiation, resulting in low rates of radiative transfer to the entire scrap charge. In addition, convective heat transfer to the interior of the scrap charge is limited by low circulation of gases within the scrap.

A typical reverberatory furnace is charged with approximately 250 tons of scrap and about 100 tons of liquid metal in order to maintain a 24-hour operating cycle; the melting portion of the cycle is 8 hours. This represents an average “melt-in” rate of cold scrap of about 31 tons per hour (Wechsler and Gitman 1991). The reverberatory furnace is charged by fork-lift trucks or by charging machines. Impurities are removed during melting by air oxidation and skimming away the resultant slag. The oxygen content of the melt is then reduced to the desired level (e.g., 0.03% to 0.04%) by adding a hydrocarbon source (e.g., natural gas) and the copper is cast into shapes such as cakes, billets, or wire-bar.

In some cases melting of copper scrap in a reverberatory furnace may be the only step in the refining process. At Reading Tube Co., for example, No. 1 copper scrap is the sole feed. All of the incoming scrap is visually inspected for known forms of suspect copper. An in-depth visual inspection is made of selected samples from the scrap; chemical analyses are taken from samples to screen for impurities. (The scrap is not monitored for radioactivity.) The scrap is charged into a 200-ton reverberatory furnace,<sup>6</sup> melted, and blown with air or oxygen to oxidize impurities. The oxide slag is skimmed from the melt. The melt is covered with charcoal and “poled” to remove oxygen. In the poling process, green hardwood logs are thrust into the molten copper bath, where the hydrocarbons react with the oxygen to form CO/CO<sub>2</sub>. The molten copper is then laundered. In this process the copper flows under charcoal into a ladle which is covered with a carbon-based product. The laundering removes additional oxygen from the melt. Final deoxidation is promoted by the addition of phosphorus; the melt is cast into billets for subsequent

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<sup>6</sup> One heat per day is typically produced. The furnace undergoes an annual maintenance shutdown. Reading also operates a shaft furnace, which can produce 100 tons per day.

fabrication into tubing (Reading 1999). The slag is sold to an outside processor for recovery of additional copper values. Offgases from the furnace pass through an after-burner to convert CO to CO<sub>2</sub> and to destroy any hydrocarbons; they are then exhausted through a stack. Stack offgas is monitored for total particulates, opacity, and SO<sub>2</sub>.

### **Electric Arc Furnace**

The electric arc furnace (EAF) is also used in secondary copper smelting <http://www.halstead.com> (5/26/99). At Halstead Industries (now part of Mueller Industries, Inc.) in Wynne, Arkansas, bales of copper scrap, cathode sheets, or copper ingots (from Codelco in Chile) are preheated with natural gas to about 1,000°F and charged into a 16,000-volt EAF<sup>7</sup>. In the EAF, the copper is melted and heated to between 2,200-2,300°F and then poured into a graphite-covered launder at a rate of 640 pounds per minute. Phosphorus pellets are added to the molten copper stream for deoxidation<sup>8</sup>. The copper flows from the launder to the casting machine, where four logs, each 9 inches in diameter and 25 ft long, are simultaneously cast at a rate of about 8 inches of ingot length per minute. The logs weigh 6,160 lb each. The launder then swings to a second set of molds while the logs produced from the first set of molds are raised from the casting pit under the molds and transferred with an overhead crane to the billet cutter. At the billet cutter each log is sawed into 14 extrusion billets, each 20.25 inches long and weighing 420 lb.

The EAF is rated at 72 tons and produces 310 to 330 tons per day (Blanton 1999). The charge is 75% to 80% scrap and 20% to 25% cathodes or ingots. Incoming scrap is screened with a Geiger counter for radioactivity. Plant procedures call for an alert at twice background and automatic rejection of the shipment at three times background. In the past four to five years there have been two alarms, both traceable to truck drivers who had been treated with radioisotopes. The furnace is equipped with a baghouse for dust collection. The dust generation rate is about 5 lb/ton and the dust contains 73% to 76% copper, some zinc, small amounts of iron and tin, and about 0.1% to 0.15% lead. Significant carbon, attributable to melt poling, is also present. Slag is skimmed from the furnace using hand rakes. The slag contains 30% to 50% copper, considerable carbon,

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<sup>7</sup> Mueller Industries also has smelting facilities in Fulton, Mississippi where, until recently, all melting was done in a shaft furnace. They have now added a Maerz reverberatory furnace at that production location.

<sup>8</sup> The alloy produced is C12200 or Phosphorus-Deoxidized High Residual Phosphorus Copper, containing 99.9% copper (min.).

calcium from bone ash (a slagging agent), zinc, and iron oxide. Both the baghouse dust and the slag are sold to Chemetco for further processing. A metric for slag generation was not available.

### C.2.3.2 Copper Converting

The product from the smelting furnace may contain significant amounts of Fe, Sn, Pb, Zn, Ni, and S. These elements are removed either by reduction and evaporation or by oxidation. At smelting temperatures, oxides of most metals are more stable than CuO or Cu<sub>2</sub>O. Thus, from an equilibrium thermodynamics perspective, these metals would be transferred to the slag under oxidizing conditions. Impurity metals with high vapor pressures (e.g., Pb, Cd, Zn) or with high-vapor-pressure oxides (e.g., SnO, Cs<sub>2</sub>O, P<sub>2</sub>O<sub>3</sub>) may volatilize and be collected in the zinc-rich dust. Tin is recovered from baghouse dust and used as tin/lead alloy for solder, and zinc is recovered and converted to ZnO for the pigment industry (Göckman 1992).

The conversion process employs either a Peirce-Smith converter or a top blown rotary converter (TBRC). Oxygen-enriched air or pure oxygen is used for the removal of impurities (Davenport 1986; Roscrow 1983).

The charge is melted under reducing conditions to avoid premature oxidation of copper. Lead, tin, and zinc are also reduced to metals. Zinc-rich dust is collected in a baghouse. Iron reacts with silica flux to form a silicate slag.

The furnace is then run in an oxidizing mode using air or oxygen. The remaining iron, zinc, tin and lead are removed. When processing black copper produced from scrap in a converter, the converter must be “blown hard” to remove nickel, tin, and antimony from the melt. This results in a slag containing over 30% copper. The slag is returned to the blast furnace for copper recovery (Opie et al. 1985). The resultant converter product is blister copper (~96% Cu). A typical furnace can produce from 4,000 to 15,000 tons per year of blister copper (O’Brien 1992). Based on metal content, the baghouse dust may be shipped to zinc smelters or to tin and lead refiners for metal recovery.

The composition of the blister copper, the slag, and the baghouse dust from a converter operation based on secondary copper smelting is summarized in Table C-8.

Table C-8. Composition of Converter Products from the Smelting of Copper Scrap (%)

Element	Blister Copper	Slag	Baghouse Dust
Cu	94 - 96	30 - 35	2 - 3
Ni	0.5 - 1.0	10 - 15	0.5 - 1.0
Sb	0.1 - 0.3	0.5 - 1.5	0.5 - 1.5
Sn	0.1 - 0.2	2 - 4	10 - 20
Fe	0.1 - 0.3	20 - 25	0.5 - 1.0
Zn	0.05 - 0.1	1.0 - 1.5	25 - 35
Pb	0.05 - 1.0	2.5 - 4.0	20 - 25

Source: Opie et al. 1985

### C.2.3.3 Fire Refining

The blister copper from the converter is then processed in an anode furnace, which is generally some type of reverberatory furnace. Anode production is the last processing step prior to electrolytic refining and is called “fire refining.” Sulfur and other readily oxidizable elements are removed by air oxidation. The dissolved oxygen is then removed from the melt by reaction with hydrocarbon gases prior to anode casting. During fire refining, the melt is first saturated with O<sub>2</sub> (about 0.8 to 0.9% O) and the oxygen is then decreased to about 0.2%. Oxidized impurities are collected in the slag, which is recycled either on-site or at another refinery.

The anodes are then cast in copper molds on a rotating horizontal wheel. Anode thickness is controlled by weighing the copper poured. The anodes contain about 99.5% copper with impurities such as Ag, As, Au, Bi, Fe, Ni, Pb, Sb, Se, and Te (Kusik and Kenahan 1978, Davenport 1986). Garbay and Chapuis (1991) list the composition of fire-refined anodes produced from a French smelting operation in a 250-t reverberatory furnace, as listed in Table C-9.

Schloen (1987) summarized typical anode chemistries at nine U.S. electrolytic copper refineries which were operating at the time. Results of this survey are presented in Table C-10.

### C.2.3.4 Electrolytic Refining

The final stage in copper purification employs an electrolytic refining process that yields copper which may contain less than 40 ppm of metallic impurities (Ramachandran and Wildman 1987).

During electrorefining, copper anodes and pure copper cathode starter sheets are suspended in a  $\text{CuSO}_4\text{-H}_2\text{SO}_4\text{-H}_2\text{O}$  electrolyte, through which an electrical current is passed at a potential of about 0.25 Vdc. The electrolytic refining process requires 10 to 14 days to produce a cathode weighing about 150 kg. During electrolysis the copper dissolves from the anode and deposits on the cathode. Impurities such as Au, Ag, and other precious metals, as well as Pb, Se, and Te collect in the anode slimes<sup>9</sup>. These anode slimes are collected and sent to a precious metals refinery (Davenport 1986). Other elements such as Fe, Ni, and Zn dissolve in the electrolyte<sup>10</sup> and are removed from the copper electrolysis cells in a bleed stream. The bleed stream is sent to “liberator” cells, where the solution is again electrolyzed and soluble copper is plated out on insoluble lead anodes. The bleed stream is then treated for  $\text{NiSO}_4$  recovery by concentrating the solution in evaporator vessels, where  $\text{NiSO}_4$  crystals precipitate. The remaining liquor is called “black acid.” Both the  $\text{NiSO}_4$  and the black acid are typically salable products (Kusik and Kenahan 1978).

Table C-9. Composition of Anodes Produced in a 250-t Reverberatory Furnace (ppm)

Ag	600	Sn	400	Bi	20
As	1,110	Sb	250	Fe	50
Pb	2,200	Se	100	Zn	100
Ni	500	Te	100	S	10

Source: Garbay and Chapuis 1991

Note: Balance Cu

The processing conducted at the ASARCO's Amarillo copper refinery (Ramachandran and Wildman 1987) is illustrative of electrorefining operations. Blister copper is shipped to the refinery in solid bottom gondola rail cars, which are unloaded either in a storage area or at the Anode Casting Department. Blister copper from the storage area is transferred to the Anode Casting Department via 11-ton fork lifts. Usage of blister copper is 8,500 tons per month (tpm). Number 2 copper scrap is received loose in box cars or trucks. The scrap is sampled and briquetted into bales which measure about  $40 \times 36 \times 17$  inches. Scrap usage is up to 6,000 tpm. The blister copper and the scrap are melted in a 350-ton Maerz tilting reverberatory furnace,

<sup>9</sup> According to U.S. patent 4,351,705, a typical slimes composition is 5-10% Cu, 4-8% Ni, 6-8% Sb, 15-25% Sn, 5-12% Pb, 0-2% Ag, and 4-8% As.

<sup>10</sup> According to Davenport (1986), As, Bi, Co, Fe, Ni, and Sb report to the electrolyte.

which operates on a 22-hour cycle. Copper for anodes, each weighing about 765 pounds, is poured into molds in a casting machine. The finished anodes are transferred to the tankhouse with a 20-ton straddle carrier. The refinery also uses a 50 ton per hour shaft furnace to remelt anode scrap from outside sources and reject anodes. Output from the shaft furnace is transferred to a 15-ton holding furnace, which feeds the same casting wheel as used with the reverberatory furnace. Monthly anode production is about 22,000 tons. Typical anode chemistry is:

- Cu ..... 98.6 - 99.4%
- Ni ..... 0.04 - 0.08%
- Sb ..... 0.05 - 0.08%
- As ..... 0.03 - 0.09%
- Se ..... 0.06 - 0.07%

The tankhouse contains six independent modules, each with its own rectifier, circulation system, reagent system, and operating crew. Each module contains 400 cells. The annual output of the plant is about 460,000 tons. Additional anodes required to maintain tankhouse operation at capacity are obtained from external sources.

A typical analysis of the cathode copper is:

- Cu ..... 99.96%
- S ..... 6 ppm
- Se ..... <1 ppm
- Sb ..... 1 ppm
- As ..... 1 ppm
- Bi ..... 0.2 ppm
- Fe ..... 2 ppm
- Nickel ..... 2 ppm
- Pb ..... <1 ppm
- Sn ..... <1 ppm
- Zn ..... < 3ppm

Table C-10. Anode Compositions at Various U.S. Electrolytic Copper Refineries

Element/ units	AT&T Nassau Metals Gaston, S.C.	Cerro Copper Products Co. East St. Louis, Ill.	Copper Range Co. White Pine, Miss.	Kennecott Refining Corp. Baltimore	Kennecott Utah Refinery Bingham Canyon, Utah	Magma Copper Co. San Manuel, Ariz.	Phelps Dodge Refining Corp. El Paso, Tex.	Southwire Copper Division Carrollton, Ga.	ASARCO Amarillo Copper Refinery Amarillo, Tex.
Cu %	99.2	99.6	99.5-99.8	99.63	99.6	99.78	99.5	99.3	99.3
Ag ppm	120	210	700	435	403	175	225-300	600	1,200
Se ppm	50	20	25	490	500	415	200-450	--	600
Te ppm	50	130	--	69	140	6	25-50	20	100
As ppm	50	100	200	500	560	24	25-50	500	400
Sb ppm	350	80	50	210	50	73	35-50	700	550
Bi ppm	50	20	5	41	33	3	5-15	30	45
Pb ppm	1,500	1,600	80	380	140	63	15-150	1,000	500
Ni ppm	1,500	500	150	510	220	121	100-700	3,000	1,700
O <sub>2</sub> ppm	2,000	1,200	1,000-1,500	1,228	1,960	900-1,200	1,400-2,800	2,000	1,600

Source: Schloen 1987

A continual bleed of electrolyte is taken from the electrorefining cells to a separate building containing copper-removal cells. Here the copper is passed through a number of primary liberator cells plumbed in series, where the copper content of the electrolyte is reduced from 40 to 20 g/L. The cathodes from these primary cells are returned to the Anode Casting Department for recasting into new anodes. A portion of the partially purified liquor is returned to the main tankhouse and the balance is sent to secondary recovery cells, where the copper content of the electrolyte is further reduced to about 1 g/L. The cathodes from the secondary cells may be returned to the Anode Casting Department or shipped to a smelter in El Paso, Texas for reprocessing.

The treated electrolyte, which contains 15 - 20 g/L of Ni, is processed through one of two submerged combustion evaporators to produce NiSO<sub>4</sub>. A single evaporator can produce about 115 tpm of NiSO<sub>4</sub> on a dry-weight basis<sup>11</sup>. The black acid remaining after nickel removal is either returned to the tankhouse for use in acid makeup or is used to leach the slimes. The crude nickel sulfate, which contains about 5% H<sub>2</sub>SO<sub>4</sub> and 3% H<sub>2</sub>O, is shipped to nickel producers. Slimes are processed at the electrorefinery.

#### C.2.3.5 Melting, Casting, and Use of Cathodes

The cathodes are washed, melted, and cast into shapes for fabrication and use. The melting is usually done in a vertical shaft furnace in which stacks of cathodes are charged near the top and melt as they descend, heated by combustion gases. The operation is continuous, and the molten copper may be cast and rolled to form rod for wiremaking, or into slabs and billets for other wrought products.

#### C.2.3.6 Slag Handling

The slags from the copper converters and the anode furnaces are rich in copper and are returned to the smelting furnace for recovery of additional copper values. The smelting furnace slag is stored or discarded in slag piles on site. Some slag is sold for railroad ballast and for blasting grit (U.S. EPA 1995). Most of the radioactive contaminants would end up in the slag because they tend to be more easily oxidized than copper.

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<sup>11</sup> If the plant processes 460,000 tons of copper anodes containing 0.08% Ni and produces 92% NiSO<sub>4</sub>, the nickel sulfate production would be about 88 tpm if all the nickel forms NiSO<sub>4</sub>, which in turn contains 38% Ni by weight.

### C.2.3.7 Offgas Handling

Offgases from the converters at primary producers are collected by a hood system and processed through an emission control system, which typically consists of an electrostatic precipitator (ESP) and a wet scrubber<sup>12</sup>. The scrubbed gas is processed through an acid plant and converted to sulfuric acid. Since secondary producers do not handle high sulfur matte, they do not have acid plants in their systems.

### C.2.3.8 Illustrative Secondary Smelter

Operations at the Southwire Company in Carrollton, Ga. are briefly described to indicate the complexity and variability of the operations at a large secondary refiner. Examples of the types of scrap handled by Southwire include blister copper, spent and reject anodes, No. 1 copper scrap, No. 2 copper scrap, No. 3 copper scrap, and miscellaneous copper-bearing materials (e.g. bronze, brass, and small motors) <[www.southwire.com/copper/recovery.htm](http://www.southwire.com/copper/recovery.htm)> (2/24/99). Southwire has a fixed NaI scintillation detector system built by Eberline to monitor incoming trucks for radioactive contamination. The system has alarmed three or four times—once by radon in propane from a Texas salt dome (McKibben 1999).

Southwire uses a blast furnace to process low-grade scrap, a top-blown rotary converter to process the blast furnace output into blister copper, a reverberatory furnace to melt No. 2 scrap, and a shaft furnace to melt and refine blister copper and No. 1 scrap and produce anodes. The high copper slags from the other furnaces are returned to the blast furnace for the recovery of additional metal values. The blast furnace slag is granulated, dried, and screened. It is sold to the roofing industry for use in shingles (Gerson 1999). The Southwire flowsheet is shown in Figure C-3 (McDonald 1999).

The brick plant in Figure C-3 was scheduled to be replaced by a new central mixing facility (Capp 1997). In the new facility, baghouse dust from the Maerz reverberatory furnace, the anode shaft furnace, the anode holding furnace, and the slag plant are collected in dust-tight tote bins. When the tote bins are full they are transported by fork-lift truck to the central mixing facility. Tote bins are filled approximately once per 12-hour shift from the reverberatory furnace

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<sup>12</sup> While some sources have suggested that scrubber blowdown at primary copper facilities is RCRA-regulated waste (K064), this is not the case. In a 1990 decision, a federal district court remanded the K064 listing to EPA for reconsideration. No further action has been taken by the Agency. The wastes may be characteristically hazardous due to acidity or metals content.

baghouse, once per shift from the slag plant baghouse, and once every one to three days from the other sources. Dust is transported from the tote bin via an enclosed screw auger to a 200 ft<sup>3</sup> storage silo (called a day bin), which holds about a three-day inventory. The dust is then moved by a second enclosed screw auger to an agglomeration unit with a design capacity of 20 tons per hour (tph), where water is added and a paste is produced. This paste is transferred to a wet bin for storage until the product is needed for feed to the blast furnace. When required, the paste is moved with a front-end loader to the blast furnace charge beds, where it is blended with other feed materials. The central mixing facility has an annual design input of about 51,100 tons per year (TPY) of baghouse dust. The facility design calls for limiting emissions through two low stacks (18 and 20 feet above grade) to 1.64 tpy of particulate material with the following indicated contaminants:

- As ..... 0.07 tpy
- Cr ..... 0.05 tpy
- Se ..... 0.05 tpy
- Cd ..... 0.004 tpy
- Ni ..... 0.004 tpy
- Sb ..... 0.000 tpy
- Co ..... 0.000 tpy
- Mn ..... 0.000 tpy
- Be ..... 0.000 tpy

These estimates were based on the analysis of baghouse fines.

Each furnace has at least one baghouse and some have a backup. Dust from the blast furnace is disposed of in a hazardous waste landfill because of Cd, Pb, and other heavy metals. Dust from the converter is sold to an overseas customer, who recovers metal values such as Pb, Sn, and Zn. Dust from the reverberatory furnace and the shaft furnace is returned to the process as described above. It is difficult to obtain a figure of merit for dust generation because it varies significantly with the type of scrap being processed. For example, a high-brass furnace charge will generate more zinc dust.

# COPPER WIRE MANUFACTURING

C-26

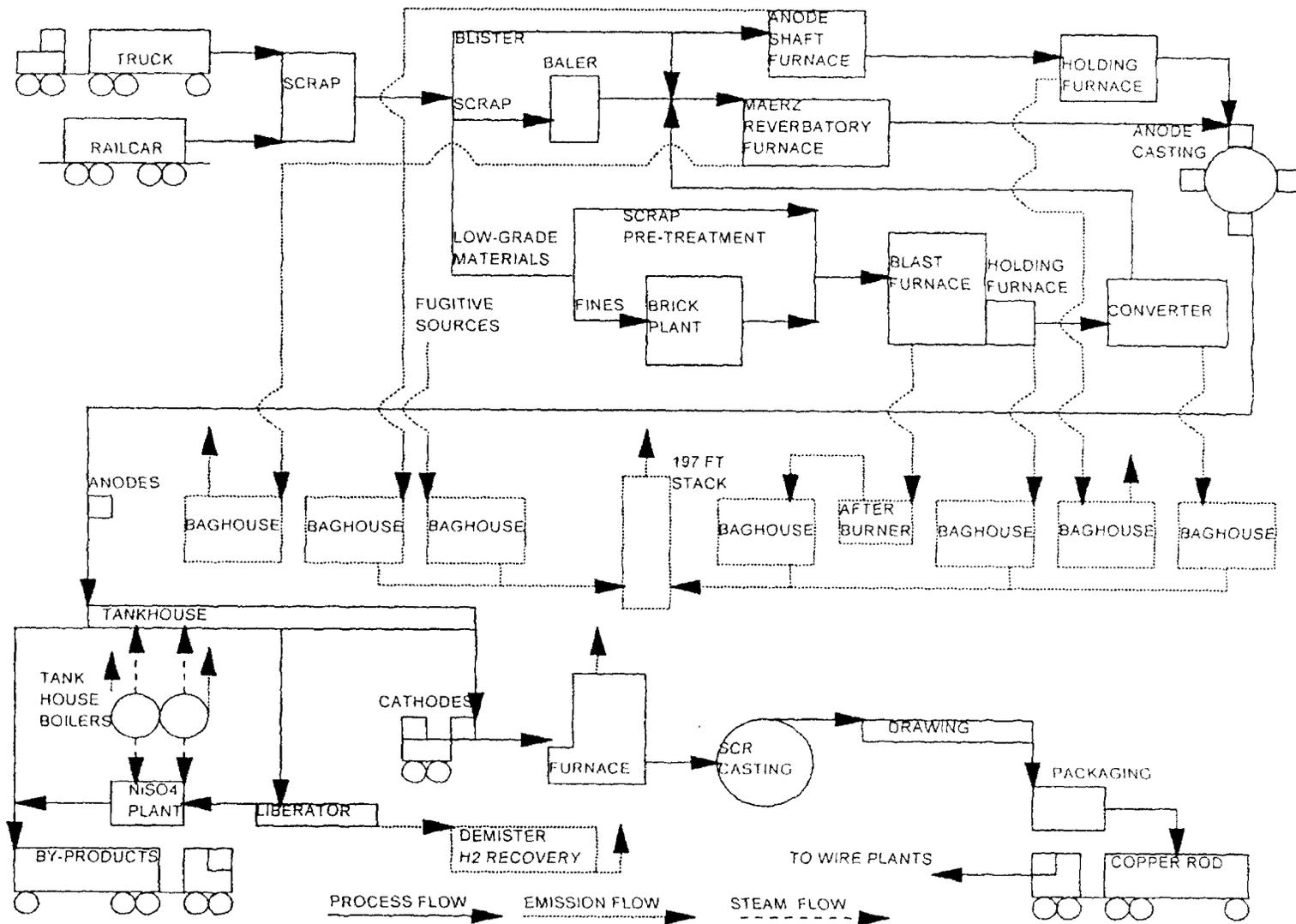


Figure C-3. Flow Diagram of the Copper Division of Southwire (CDS)

Anodes are electrolytically refined. The anode slimes are sold to an offshore processor for precious metal recovery. Copper is removed from the electrolyte bleed by electroplating. The solution is then evaporated. Nickel sulfate is crystallized and recovered for sale.

Cathodes from the electrorefining operation are melted in a shaft furnace and cast into copper rod. In 1998, the output of the rod-mill shaft furnace was about 342,000 tons (McDonald 1999).

Operations at Chemetco, a secondary smelter in Hartford, Illinois are somewhat different. Chemetco has four 70,000 lb reverberatory furnaces and four top-blown rotary converters to process scrap (Riga 1999). They process scrap ranging from high-grade copper wire to low-grade slags and skims. Slags are sold for railroad ballast, road beds, and asphalt shingles. Anodes are sold to Asarco for electrorefining.

#### C.2.4 Brass and Bronze Ingot Production

As shown in Figure C-1, about 10% of copper-base scrap is consumed by brass and bronze ingot makers. At the ingot manufacturer, scrap is melted in a reverberatory furnace. Fluxing agents such as borax and sodium nitrate are added. Alloying agents such as tin may also be included in the furnace charge. Zinc evolved in the melting process is collected in a baghouse. Slag is either returned to a smelter for reprocessing or shipped for disposal (Kusik and Kenahan 1978).

Aluminum bronze is melted in gas- or oil-fired crucible furnaces, coreless induction furnaces, or in reverberatory furnaces (for very large castings) (U.K. CDA 1999). The furnace charge typically involves addition of cathode copper, aluminum (either as ingot or a 50% Al-50% Cu master alloy), and iron and nickel (either in elemental form or as a master alloy). Process scrap is generally added when the ingots are remelted to produce the final castings but may be added at the end of the alloying schedule. During melting, most of the copper together with the iron and nickel are introduced into the furnace under a charcoal blanket and the melt is heated to about 1,300°C. The remaining copper is then added, the charcoal is removed and the aluminum is charged. A small amount of cryolite or fluoride flux is then stirred into the melt to clean entrapped metal from the dross before pouring the melt into ingot molds.

#### C.2.5 Brass Mills

Brasses are alloys of copper with up to 40% zinc. Other alloying elements such as Al, Fe, Mn, Pb, and Sn may be added at levels of up to a few percent of each metal, depending on the specific

alloy being produced. As shown in Table C-11, brass mills are major consumers of yellow and red brass scrap. An example is the Chase Brass and Copper Company, which produces brass rod primarily from scrap. Chase currently has an annual capacity of about 300 million lb per year and is expanding to 400 million lb per year. The scrap is melted in four induction furnaces and cast into logs, which are 23 ft long and 10 inches in diameter. About 80% of their scrap requirements are obtained through purchase and tolling arrangements with their customers. In 1997 there was a price differential of 5 cents per pound between the metal selling price to the customer and the metal buying price (i.e., the scrap price) from the customer. The balance of their requirements are purchased from scrap dealers at the free-market price. Chase uses hand-held detectors to check scrap from unknown (i.e., open-market) sources for radioactivity. They have had no instances where any activity has been detected in the scrap. Several million pounds are typically in inventory at the plant site. A baghouse system is used to collect dust from the furnace offgas. Dross is removed from the furnace and run through a vibratory screening system to collect metal for internal recycle. Both the undersize from the dross processing and the baghouse dust are drummed and sold to an off-site reprocessor (Warner 1999, Woodserman 1999). The reprocessor treats these waste streams with mineral acids and then crystallizes various metal salts from the solutions. Typically, the salts are sold to the steel industry for use in fluxes. Chase seldom uses copper scrap in its melting operations. Use of copper in the furnace charge requires a higher melting temperature, which increases zinc losses from the melt. Chase does not have a figure of merit for baghouse dust production. The value is quite variable depending on the alloy being melted, the quantity of scrap in the furnace charge, etc.

Olin Brass in East Alton, Ill. produces 60 to 70 different copper and brass alloys. Most of the scrap used is either run-around (internal) scrap or customer returns (either direct or handled by a broker). A portable spectrometer may be used to check the chemistry of an incoming truckload of scrap. Occasionally, pure copper is used for selected products. Melting is done in small induction furnaces that feed a large holding furnace. The furnace charge is typically baled scrap. Most Olin alloys are cast by the direct chill method, in which multiple ingots are cast simultaneously. Each rectangular cross-section ingot is about 25-ft long and weighs 18,000 lb. The ingots are reduced to sheet and strip via a series of hot and cold rolling operations (Olin 1995). Furnace offgas is processed through cyclone separators and a baghouse. During melting, dross formation is not intentionally promoted. However, use of highly reactive alloying additions may enhance dross formation. Dross disposition practices, which are proprietary, are designed to maximize process economics (presumably by using some sort of recycling). The same considerations apply to treatment of baghouse dust (Shooter 1999).

Table C-11. Consumption of Copper-Base Scrap in 1997

Scrap Type and Processor	Consumption (t)
<b>No. 1 wire and heavy:</b>	
Smelters, refiners, and ingot makers	149,000
Brass and wire-rod mills	413,000
Foundries and misc. manufacturers	35,800
<b>No. 2 mixed light and heavy:</b>	
Smelters, refiners, and ingot makers	230,000
Brass and wire-rod mills	34,900
Foundries and misc. manufacturers	2,770
<b>Total unalloyed scrap:</b>	
Smelters, refiners, and ingot makers	379,000
Brass and wire-rod mills	448,000
Foundries, and miscellaneous manufacturers	38,600
<b>Red brass:<sup>a</sup></b>	
Smelters, refiners, and ingot makers	58,300
Brass mills	8,780
Foundries and miscellaneous manufacturers	10,100
<b>Leaded yellow brass:</b>	
Smelters, refiners, and ingot makers	28,800
Brass mills	404,000
Foundries and miscellaneous manufacturers	1,930
<b>Yellow and low brass: all plants</b>	53,900
<b>Cartridge cases and brass: all plants</b>	66,800
<b>Auto radiators</b>	
Smelters, refiners, and ingot makers	72,200
Foundries and miscellaneous manufacturers	4,470
<b>Bronzes</b>	
Smelters, refiners, and ingot makers	12,100
Brass mills and miscellaneous manufacturers	14,900
<b>Nickel-copper alloys: all plants</b>	17,800
<b>Low-grade and residues</b>	
Smelters, refiners, and miscellaneous manufacturers	87,100

Source: Edelstein 1998

<sup>a</sup> Includes composition turnings, silicon bronze, railroad car boxes, cocks, and faucets, gilding metal, and commercial bronze.

Table C-11 (continued)

Scrap Type and Processor	Consumption (t)
<b>Other alloy scrap<sup>b</sup></b>	
Smelters, refiners, and ingot makers	38,400
Brass mills and miscellaneous manufacturers	6,570
<b>Total alloyed scrap</b>	
Smelters, refiners, and ingot makers	303,000
Brass mills	558,000
Foundries and miscellaneous manufacturers	24,100
<b>Total Scrap</b>	
Smelters, refiners, and ingot makers	682,000
Brass and wire-rod mills	1,010,000
Foundries and miscellaneous manufacturers	62,700

<sup>b</sup> Includes refinery brass, beryllium copper, and aluminum bronze.

### C.2.6 Aluminum Bronze Foundries

Aluminum bronzes may be produced from prealloyed ingots (see Section C.2.4) or from directly alloyed components. In the latter case, the copper is melted together with copper/iron and copper/nickel master alloys at 1,200°C under a charcoal cover (U.K. CDA 1999). The melt is then deoxidized with a copper/manganese alloy and the charcoal cover is removed. The manganese oxide is skimmed off at this point to prevent its subsequent reduction by aluminum. An aluminum/copper master alloy is next added in small increments. The melt is then degassed with nitrogen (which also facilitates mixing) and a small quantity of a fluoride-base flux is added to remove metal from the dross. The bronze is then cast into appropriate molds.

Melting of large charges in a reverberatory furnace may require use of a cover flux to reduce oxidation losses.

Melt temperature and melting time are kept to a minimum to control hydrogen pickup in the furnace. At 1,200°C, the hydrogen solubility in an aluminum bronze containing 8% Al is about 3.5 cm<sup>3</sup>/100 g and this increases to about 5.8 cm<sup>3</sup>/100 g at 1,400°C. (The solubility of hydrogen in pure copper at comparable temperatures is more than twice as high.)

### C.3 MARKETS

The leading consumers of refined copper are wire mills, accounting for 75% of the refined copper consumption. Brass mills producing copper and copper alloy semi-fabricated shapes are the other dominant consumers at 23%. The dominant end-users of copper and copper alloys are the construction and electronic products industries, accounting for 65% of copper end-usage. Transportation equipment, such as vehicle radiators, accounts for an end-usage of 11.6%. A passenger car typically contains 50 lb of copper wire (BHP 1997). Copper and copper alloy powders are used for brake linings and bands, bushings, instruments, and filters in the automotive and aerospace industries, for electrical and electronic applications, for anti-fouling paints and coatings, and for various chemical and medical purposes. Copper chemicals, principally  $\text{CuSO}_4$ ,  $\text{CuO}$ , and  $\text{Cu}_2\text{O}$ , are widely used in algacides, fungicides, wood preservatives, copper plating, pigments, electronic applications, and numerous special applications.

End-use markets for brass rod include:

- construction and remodeling . . . . . 48%
- industrial equipment and machinery . . . . . 30%
- electrical and electronics . . . . . 8%
- transportation equipment . . . . . 8%
- exports . . . . . 4%
- consumer durables . . . . . 2%

Typical products include plumbing fixtures, industrial valves and fittings, welding and cutting equipment, cable and electronic connectors, gas grill components, brake hose assemblies, and decorative hardware.

#### C.3.1 Scrap Prices

Scrap prices are related to the refined copper price, but the price spread must be sufficient to allow for collection, sorting, shipping, chopping, etc. If the price spread is too narrow, the processor cannot charge enough for the end product, which also is determined by the refined copper price, to make a profit. When refined copper prices are high, more copper scrap is offered to processors. If refined copper prices are low, less scrap enters the market. As the gap between

scrap price and refined price narrows, the processing cost may make the scrap uneconomical (Carlin et al. 1995).

### C.3.2 Scrap Consumption

Copper-base scrap consumption in 1997 by type of scrap and by processor is summarized in Table C-11 (Edelstein 1998). The total consumption of 1,755,000 t is greater than the total of 1,370,000 t shown in Table C-4 because the latter table is based on the copper content of the scrap while the former is based on the gross weight of the copper-base alloys. Both of these tables are based on copper-base scrap, while Table C-3 includes other alloys where copper is not the primary alloying element. Table C-11 emphasizes the diversity of copper scrap uses. Unalloyed scrap is consumed by smelters, refiners, ingot makers, brass mills, wire-rod mills, and foundries. While about 63% of alloy scrap is consumed by brass mills, a significant fraction is also processed by ingot makers, smelters, refiners, and foundries.

It is worth noting that environmental restrictions on lead associated with copper pose obstacles to recycling certain copper alloys, particularly some brasses. The addition of up to 8% lead in brass castings and rod improves machinability and casting characteristics. New drinking water standards may require elimination of most of the lead from brass plumbing fixtures (Carlin et al. 1995). As can be seen in Table C-11, leaded brass is a major component of copper-base scrap recycling.

## C.4 PARTITIONING OF CONTAMINANTS

This section discusses the manner in which impurities partition during the various metallurgical operations involved in the refining of copper scrap.

The main application of copper is as an electrical conductor. As such, extremely high purity levels are required to maintain low electrical resistance. As little as 0.08% iron or 0.05% phosphorus will reduce the conductivity of copper by 33% (CDA 1998b). Typical output from the cathode furnace may be electrolytic tough-pitch copper which contains a minimum 99.90% copper or oxygen-free copper, which contains a minimum of 99.95% copper. Thus, the aim of copper refining is to remove most of the impurities from the metal. The following sections discuss the expected distribution of contaminants in scrap that is introduced into the copper processing cycle (see Figure C-2). The expected partitioning from scrap which is introduced into brass mills, foundries, and the like will be discussed in a later section.

## C.4.1 Partitioning During Copper Refining

### C.4.1.1 Thermochemical Considerations

Most impurities in copper scrap introduced into blast furnaces, converters, or anode (fire refining) furnaces will tend to be oxidized during processing and removed with the slag. Theoretically, this will include all oxides whose free energies of formation per gram-atom of oxygen are more negative than that of CuO. The free energy of formation of CuO at 1,500 K (1,227°C) is about -6 Kcal/gram-atom of oxygen (Glassner 1957). Oxides of metals such as Po, Te, and the platinum group (Pt, Pd, Rh, Ir) are less stable than CuO and the respective metals should remain with the copper. Cs<sub>2</sub>O boils below 1,000 K and would be volatilized. Other species with low boiling points such as Cd, Po, Ra, Se, and Zn may also be partially volatilized (see Table E-3). Relevant free energy data for various oxides are summarized in Table C-12. Of the elements whose oxides are listed in this table, only Ag and Ru are expected to remain in the copper under equilibrium conditions.

Copeland et al. (1978) calculated the partition ratios between copper and an oxide slag for several contaminants, based on free-energy data. The authors assumed that: (1) the weight of the slag was 10% of the weight of the metal, (2) the activity of the copper oxide in the slag was 0.1, and (3) the activity of the contaminant oxide in the slag was 0.01. Henry's Law constants for the contaminant and the contaminant oxide were assumed to be unity (i.e., ideal solution behavior). The partition ratio was defined as the weight of the contaminant in the slag divided by the weight of the contaminant in the ingot. Calculated partition ratios at 1,400 K are summarized in Table C-13. These calculations suggest that all the elements listed except cobalt will partition to the slag and that concentrations of most of these contaminants in the copper will be very low.

However, blister copper leaving the converter is reported to contain small amounts of impurities such as As, Bi, Fe, Ni, Pb, Sb, Se, Te, and precious metals (Davenport 1986). This emphasizes that predictions based on thermochemical calculations and vapor pressures are only guidelines to impurity behavior during processing.

### C.4.1.2 Experimental Partitioning Studies

Some experimental work has been done to measure partitioning of radionuclides during copper smelting. Heshmatpour et al. (1983) found that plutonium strongly partitioned to the slag, as would be expected from thermodynamic considerations. Three tests were conducted, in which

500 ppm of PuO<sub>2</sub> was melted with 200 grams of copper in recrystallized alumina crucibles at 1,400°C. The slag weight was 10% of the metal weight. Slags included a borosilicate composition (80% SiO<sub>2</sub>, 13% B<sub>2</sub>O<sub>3</sub>, 4% Na<sub>2</sub>O, 2% Al<sub>2</sub>O<sub>3</sub>, 1% K<sub>2</sub>O), a blast furnace composition (40% CaO, 30% SiO<sub>2</sub>, 10% Al<sub>2</sub>O<sub>3</sub>, 15% Fe<sub>2</sub>O<sub>3</sub>, 5% CaF<sub>2</sub>) and a high silica composition (60% SiO<sub>2</sub>, 30% CaO, 10% Al<sub>2</sub>O<sub>3</sub>). The respective partition ratios (defined as the ratio of total Pu in the slag to total Pu in melt) were 3,225, 157, and 107. In each case less than 1 ppm of Pu remained in the copper. In the last two cases, a significant fraction of the input PuO<sub>2</sub> was not accounted for, rendering these values suspect.

Copeland and Heestand (1980) measured the partition ratio of uranium in copper in a laboratory experiment by equilibrating copper at 1,100°C with a slag containing 0.3 wt% U. The measured partition ratio was 600, which is many orders of magnitude lower than the predicted value (see Table C-13). The final uranium concentration in the copper was 5 ppm. Other experimental details were not provided. A laboratory drip-melting experiment was also described, in which surface contaminated copper was placed on a screen and melted. The molten copper passed through the screen into a crucible below. Assay of the dross and the ingot showed that the former contained 3,400 ppm U, while the latter contained 1.4 ppm U. In a scaled-up experiment, about 40 kg of copper scrap surface contaminated with UO<sub>2</sub> was drip melted. The copper ingots contained 0.07 ppm U, while the slag contained 1,250 ppm U, resulting in a partition ratio of 18,000.

In subsequent work, Heshmatpour and Copeland (1981) conducted a series of laboratory experiments, in which 500 ppm UO<sub>2</sub> was added to small melts of copper produced with various fluxes. The samples were melted in recrystallized alumina or zirconia crucibles and held at about 1,250°C to equilibrate the melt and the slag. The results, which are summarized in Table C-14, show that the partition ratios vary from 49 to 3182.

Mautz (1975) and Davis et al. (1957) summarized the results of melting 40 heats (about 100 tons) of uranium-contaminated copper scrap with surface activities up to 150,000 dpm/100 cm<sup>2</sup> in an oil-fired reverberatory furnace with a 125-ft stack. Ten samples taken from the copper product showed uranium values ranging from <0.022 ppm to 3.1 ppm. Six slag samples contained 1,440 to 1,730 ppm of U, while two samples contained only 0.43 and 0.47 ppm. No explanation for these low values was provided, although it is possible that the copper melts from which these slag samples were taken were initially very low in U. Uranium contamination of the furnace lining was also detected. Activity in the stack averaged  $4 \times 10^{-11}$  μCi/cc. No air activity

was detected outside the furnace in excess of  $1.7 \times 10^{-12} \mu\text{Ci}/\text{cm}^3$ , which is 10% of the MPC value listed in NBS Handbook 52 for a controlled area. Samples collected to detect fallout showed no measurable uranium contamination of areas inside or outside the furnace building.

Table C-12. Standard Free Energies of Formation for Various Oxides at 1,500 K

Metal Oxide	$-\Delta F^\circ$ (Kcal/g-atom O)
Ag <sub>2</sub> O	decomposes at 460 K
RuO <sub>4</sub>	1.9
CuO	5.8
Cs <sub>2</sub> O	9.4
Cu <sub>2</sub> O	14.2
PbO	19.1
TcO <sub>2</sub>	19.9
Sb <sub>2</sub> O <sub>3</sub>	26.0
CoO	26.5
NiO	26.5
FeO	38.6
ZnO	39.2
MnO	65.7
SiO <sub>2</sub>	73.4
PaO <sub>2</sub>	89.8
AmO <sub>2</sub>	89.8
NpO <sub>2</sub>	91.6
RaO	94.6
CeO <sub>2</sub>	94.6
UO <sub>2</sub>	99.0
Pu <sub>2</sub> O <sub>3</sub>	99.9
SrO	102
ThO <sub>2</sub>	113

Source: Copeland et al. 1978

Abe et al. (1985) also conducted laboratory experiments to examine melt refining as a copper decontamination scheme. In these studies, 100 grams of metal and 10 grams of flux were melted in an alumina crucible under argon. Using a 1,550°C melting temperature, a melting time of one hour and a flux consisting of 40% SiO<sub>2</sub>, 40% CaO, and 20% Al<sub>2</sub>O<sub>3</sub>, decontamination factors

ranged from 100 for an initial uranium concentration of 10 ppm to  $10^4$  for 1,000 ppm. The final uranium concentration in the ingot appeared to be relatively insensitive to the amount of uranium introduced into the melt. This suggests that the uranium content in the melt would not be less than about 0.1 ppm under the conditions of these experiments. However, the minimum observed uranium concentration in the melt-refined ingot—0.083 ppm—is very close to the 0.075 ppm of uranium in the copper feed stock used in this experiment.

Table C-13. Calculated Partition Ratios of Various Contaminants Between Copper and an Oxide Slag at 1,400 K

Contaminant	Partition Ratio
Th	$10^{31}$
Hf	$10^{26}$
U	$10^{24}$
Np	$10^{24}$
Ti	$10^{21}$
Pu	$10^{20}$
W	$10^8$
Tc	$10^3$
Co	$10^0$

Source: Copeland et al. 1978

In another study, Ren et al. (1994) conducted a series of laboratory experiments to optimize the removal of uranium contamination from copper. Samples weighing 100 grams were doped with 238 ppm uranium and melted with various fluxes. The investigation showed that residual uranium in the copper was at a minimum when the basicity of the flux was about 1.1. The highest decontamination factors were obtained when the flux was made from a blast furnace slag with the nominal composition: 38.1%  $\text{SiO}_2$ , 41.4%  $\text{CaO}$ , 3.8%  $\text{MgO}$ , 2.6%  $\text{Fe}_2\text{O}_3$ , and 14.1%  $\text{Al}_2\text{O}_3$ . To minimize the residual uranium in the copper, the mass of flux needed to be at least 5% of the metal charge. The researchers also found that over a range of uranium concentrations of 2.4 to 238 ppm, the residual uranium content in the copper ingot was unchanged. This is the opposite of the finding of Abe et al. (1985) discussed in the previous paragraph. The maximum decontamination factor achieved in the laboratory tests was 236.

Table C-14. Partitioning of Uranium in Laboratory Melts of Copper

Sample	Metal (g)	Flux (g)	U concentration (ppm)		Partition Ratio <sup>a</sup>	Flux Composition					
			Slag	Metal		Al <sub>2</sub> O <sub>3</sub>	CaF	CaO	CuO	Fe <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>
1	100	10	934	0.13	718	25	—	25	—	—	50
2	100	10	341	0.37	92	20	—	20	—	—	60
3	100	10	411	0.11	374	15	—	15	—	—	70
4	100	10	213	0.14	152	—	—	30	5	—	65
5	100	10	265	0.54	49	10	—	20	5	—	65
6	100	10	390	0.45	87	10	—	30	5	—	55
7	100	10	1813	0.83	218	10	—	10	—	5	75
8	100	10	1273	0.04	3182	10	—	10	—	5	65
9	100	10	943	0.25	377	10	—	30	—	5	55
10	250	25	1590	1.36	117	borosilicate glass					
11	250	25	1650	0.14	1179	10	5	50	—	5	30
12	170	—	—	1.96	—	no flux					

Source: Heshmatpour and Copeland 1981

<sup>a</sup> Mass of uranium in slag divided by mass in metal

Vorotnikov et al. (1969) studied the behavior of iridium and ruthenium during the electrorefining of copper. They used copper anodes with 0.4% Ni, to which Ru-106 and Ir-192 were added. The distribution of these radionuclides during electrorefining in laboratory cells at current densities of 175 to 350 A/m<sup>2</sup> is summarized in Table C-15.

Table C-15. Distribution of Iridium and Ruthenium During Electrorefining of Copper

Current Density (A/m <sup>2</sup> )	Ir (%)			Ru (%)		
	Electrolyte	Slimes	Cathode	Electrolyte	Slimes	Cathode
175	14	84	none	65	29.8	3.8
240	15	83	none	67	27.4	3.2
350	15.5	81	none	70	20.1	3.0

Source: Vorotnikov et al. 1969

As can be seen, most of the iridium reports to the slimes, while most of the ruthenium reports to the electrolyte. The electrolyte was then decoppered at a current density of 400 A/m<sup>2</sup>; the

resultant solution was boiled to produce nickel sulfate. Distribution of the iridium and ruthenium after electrolyte purification is shown in Table C-16.

Table C-16. Distribution of Iridium and Ruthenium after Electrolyte Purification

Product	Ir (%)	Ru (%)
Regenerated Copper	None	5.0
Copper Sponge	Undetermined	21.0
Nickel Sulfate	Undetermined	12
Electrolyte	90	70

Source: Vorotnikov et al. 1969

Even after purification of the electrolyte, most of the iridium and ruthenium remain in that process stream.

#### C.4.1.3 Proposed Partitioning of Contaminants

##### **Blast Furnace Smelting**

Based on the information presented in Table C-5, expected partition ratios of contaminants during the processing of low-grade copper scrap in a blast furnace were developed using the studies of Opie et al. (1985) and Nelmes (1984). The study of Kusik and Kenahan (1978), also included in Table C-5, was not used to estimate partition ratios since those authors did not include information on slag compositions. The slag resulting from the blast furnace operation characterized by Opie et al. (1985) in Table C-5 is rich in recoverable metals. These authors describe a processing step in which the blast furnace slag is further treated in a EAF, to which 2% coke is added as a reductant (see Section C.2.3.1, Table C-6). The slag from this step is assumed to be granulated and sold. Slags generated from downstream operations are returned to the blast furnace for recovery of additional metal values. By assuming that the metal streams and the dust streams are combined, overall observed partitioning from the blast furnace/EAF processing can be calculated from the Opie study. This additional step was not used in analyzing the Nelmes data. The results of the partitioning studies are summarized in Table C-17. In developing this table, it was assumed that each 100 tons charged to a blast furnace produces 40 tons of black copper, 40 tons of slag, and 5 tons of baghouse dust (Nelmes 1984). To develop the ranges shown in Table C-17, the maximum and minimum values were selected from among the data from the various studies.

U.S. Patent No. 4,351,705 (related to the work of Opie et al. [1985]) provides information on the partitioning of silver. In one example from the patent, 1,455 tons of converter slag containing 17.2 oz/ton Ag were smelted in a blast furnace to produce 420 tons of black copper containing 43.2 oz/ton Ag and an unspecified quantity of blast furnace slag containing 0.81 oz/ton Ag. When the blast furnace slag was cleaned in an arc furnace, the silver content was reduced to 0.5 oz/ton. Based on additional information included in the patent, it can be estimated that approximately 1,170 tons of blast furnace slag were produced. The silver input to the smelting process from the converter slag was 25,000 oz; the silver output was 18,100 oz to the black copper and 950 oz to the blast furnace slag, leaving about 6,000 oz unaccounted for. In order to achieve a material balance, it is assumed here that the unaccounted material is contained in the baghouse dust. Using methodology similar to that for other metals during the slag cleaning process, one can estimate that the 950 oz of silver in the blast furnace slag are distributed as follows:

- black copper from EAF ..... 410 oz
- slag from EAF ..... 540 oz
- baghouse dust from EAF: set to zero (the quantity will be small relative to that collected in the converter baghouse).

These calculations provide the basis for the silver partition fractions in Table C-17.

Table C-17  
Observed Partition Fractions in the Melting of Low-grade Copper Scrap in a Blast Furnace

Element	Metal		Dust		Slag	
	Min.	Max.	Min.	Max.	Min.	Max.
Cu	0.99	0.99	0.0023	0.0039	0.0027	0.011
Ni	0.73	0.97	0.0020	0.0053	0.023	0.27
Sb	0.80	0.84	0.056	0.060	0.10	0.14
Sn	0.89	0.91	0.028	0.066	0.019	0.068
Fe	0.14	0.24	0.00	0.00029	0.84	0.86
Zn	0.24	0.40	0.51	0.52	0.080	0.24
Pb	0.47	0.62	0.29	0.31	0.093	0.13
Cl	0	0	1.0	1.0	0	0
F	0	0	1.0	1.0	0	0
Ag	0.74	0.74	0.022	0.022	0.24	0.24

The observed partitioning during the smelting of copper scrap in a blast furnace, as summarized in Table C-17, is combined with chemical analogies for certain elements and thermodynamic predictions from Table C-12 to arrive at the proposed partitioning for the desired suite of elements. This summary is presented in Table C-18. Most of the actinides form very stable oxides and are expected to be removed from the copper and concentrated in the slag. Even if removal is not 100%, as proposed in Table C-18, when the black copper is blown in a converter, the strongly oxidizing conditions can be expected to remove residual quantities of these elements to the converter slag, which is recycled to the blast furnace.

Table C-18  
Partition Fractions of Impurities in the Melting of Low-grade Copper Scrap in a Blast Furnace

Element	Metal	Slag	Baghouse Dust	Basis for Estimate
Ag	0.74	0.02	0.24	Table C-17
Am		1.0		Table C-12
Ce		1.0		Table C-12
Co	0.73/0.97	0.023/0.27	0.0020/0.0053	Same as Ni, Table C-13
Cu	0.99/0.99	0.0027/0.011	0.0023/0.0039	Table C-17
Cs		0.10/0.20	0.80/0.90	Table C-12, WCT
Fe	0.14/ 0.24	0.84/0.86	0.00/0.00029	Table C-17
Mn	0.14/0.24	0.84/0.86	0.00/0.00029	Same as Fe
Ni	0.73/0.97	0.023/0.27	0.0020/0.0053	Table C-17
Np		1.0		Table C-12, Table C-13
Pa		1.0		Table C-12
Pb	0.47/0.62	0.093/0.13	0.29/0.31	Table C-17
Pu		1.0		Table C-12, Table C-13
Ra		1.0		Table C-12
Ru	0.99/0.99	0.0027/0.011	0.0023/0.0039	Same as Cu
Sb	0.80/0.84	0.10/0.14	0.056/0.060	Table C-17
Si		some	some	Table C-5
Sr		1.0		Table C-12
Tc	0.73/0.97	0.023/0.27	0.0020/0.0053	Same as Ni, Table C-13
Th		1.0		Table C-12, Table C-13
U		1.0		Table C-12, Table C-13
Zn	0.24/0.40	0.080/0.24	0.51/0.52	Table C-17

WCT = Author judgement

## **Converting**

Some information on the composition of the process streams emanating from a copper converter is presented in Table C-8. However, no mass balance information was available to develop estimates of partition ratios. If copper scrap is introduced directly into the converter, it is expected that partitioning will be similar to that in the blast furnace. The strongly oxidizing conditions should insure that any actinides and other strong oxide formers will be oxidized and removed with the slag. If the scrap were introduced at the blast furnace stage, removal of additional Fe, Ni, Sb, Sn, Pb and Zn would be expected, based on the information included in Tables C-5 and C-8, resulting in blister copper with fewer impurities.

## **Fire Refining and Electrolysis**

Expected partitioning of impurities in fire-refined copper and in electrorefined copper is summarized in Tables C-19 and C-21, respectively. Both fire-refined copper and electrorefined copper are included since both are used to produce end products. For example, fire-refined copper is used to produce sheet and tubing while electrorefined copper is used to produce wire. The elemental partitioning proposed in Table C-19 is appropriate for evaluating scenarios involving production for non-electrical applications where, say, No. 1 scrap is used to make a copper product such as tubing for plumbing applications or sheet for roofing. If the scrap is introduced earlier in the process then, with the exception of silver and ruthenium, which are not easily oxidized, the quantities of radioactive contaminants remaining with the metal should have been reduced during prior processing steps. The values for Ag, Fe, Ni, Pb, Sb, and Zn were developed using the data in Table C-8 for the feed composition and the data of Garbay and Chapuis (1991) is cited in Table C-9 for the chemistry of the fire-refined anodes. While the use of two unrelated data sets is a recognized problem, better data were not uncovered during the current study. This concern is ameliorated, in part, by providing a range for many of the partition factors.

As was discussed in Section C.2.3.1, a reverberatory furnace used for fire refining may not be equipped with a baghouse for dust collection. Offgas exiting the furnace after-burner may be exhausted directly through a stack. There are no NESHAPS standards for secondary copper smelters.

Brunson and Stone (1975) provide information of the composition of the anode and cathode copper, as well as anode slimes at the Southwire Co. The compositions are listed in Table C-20.

Table C-19. Partition Fractions of Impurities in the Fire Refining of Copper

Element	Metal	Slag	Offgas	Basis for Estimate
Ag	0.30/0.59	0.41/0.70		Table C-8, Table C-12, Garbay and Chapuis 1991
Am	0.001/0.01	0.99/0.999		Same as Pu
Co	0.05/0.10	0.90/0.95		Table C-12, same as Ni
Cs		0.10/0.20	0.80/0.90	Table C-12, WCT
Fe	0.02/0.05	0.95/0.98		Table C-8, Table C-12, Garbay and Chapuis 1991
Mn	0.02/0.05	0.95/0.98		Table C-12, Same as Fe
Ni	0.05/0.10	0.90/0.95		Table C-8, Table C-12, Garbay and Chapuis 1991
Np	0.001/0.01	0.99/0.999		Same as Pu
Pa	0.001/0.02	0.98/0.999		Same as U
Pb	0.22	0.73/0.78	0.00/0.05	Table C-8, Table C-12, Garbay and Chapuis 1991, WCT
Pu	0.001/0.01	0.99/0.999		Tables C-12 and C-13, Heshmatpour et al. 1983
Ru	1			Table C-12
Sb	0.08/0.25	0.75/0.92	0.00/0.05	Table C-8, Table C-12, Garbay and Chapuis 1991, WCT
Si		1		Table C-12
Sr		1		Table C-12
Tc	0.001	0.999		Table C-12 and C-13
Th	0.001/0.02	0.98/0.999		Same as U
U	0.001/0.02	0.98/0.999		Tables C-12 and C-13, Heshmatpour and Copeland 1981 (Table C-14)
Zn	0.10/0.20	0.80/0.90	0.00/0.05	Table C-8, Table C-12, WCT, Garbay and Chapuis 1991

WCT = author judgement

Table C-21 presents partition fractions of selected impurities in the electrorefining process, based on the data reported by Brunson and Stone (1975). Cobalt and manganese were assumed to behave like nickel and iron, respectively. Strontium was assumed to behave similarly to calcium. When a contaminant was identified in both the anode slimes and in the cell bleed (i.e., Fe, Sb, and Zn), the unaccounted for material was assumed to accumulate in the nickel sulfate, which is recrystallized from the cell bleed after copper is removed in the liberator cells. Detailed calculations are summarized in Appendix C-1. Ruthenium partitioning is based on data of Vorotnikov et al. (1969). Metal partitioning can also be estimated for a limited suite of elements using the data of Ramachandran and Wildman (1987) presented in Section C.2.3.4. Comparing these data with the values in Table C-21 indicates that the latter values are conservative (i.e., show slightly higher partitioning to the metal) for use in predicting radiation exposures to residual radioactive contaminants in metal.

Table C-20  
Composition of Anode and Cathode Copper and Anode Slimes at the Southwire Co.

Element	Typical Anode (%)	Typical Cathode	Anode Slimes (%)
Cu	99.50	99.99%	8.77
O	0.10	—	—
S	0.003	—	—
Pb	0.19	5 ppm	31.45
Ni	0.10	7 ppm	
As	0.005	1 ppm	0.75
Sb	0.010	1 ppm	—
Bi	0.0007	0.1 ppm	—
Au	0.0012	—	0.55
Ag	0.024	10 ppm	4.65
Se	0.031	0.5 ppm	—
Te	0.0003	1 ppm	—
Sn	0.025	1 ppm	9.28
Fe	0.025	6 ppm	1.20
Zn	0.013	—	—
Ca	—	—	1.10
Si	—	—	3.50

Source: Brunson and Stone (1975)

Note: Slimes also contain 0.001% Pt and 0.001% Pd.

The literature on the electrorefining of copper abounds with consideration of the removal of impurities typically associated with copper, including Ag, As, Bi, Ni, Pb, Sb, Se, and Te. Virtually no information was uncovered in the course of this study on actinides and fission products, which are among the possible contaminants of copper cleared from nuclear facilities. To provide a quantitative perspective on the expected behavior of these contaminants during electrorefining, recourse was taken to some general electrorefining principles. According to Demaeral (1987):

During the electrorefining of copper, anode impurities either dissolve in the electrolyte or remain as insoluble compounds in the anode slime. Elements less noble than copper such as zinc, nickel and iron easily dissolve in the electrolyte. Elements more electropositive than copper, e.g. selenium, tellurium, silver, gold, and the platinum group metals and elements which are insoluble in sulphuric acid, such as lead, are concentrated in the anode slime. A

third group of elements, comprising the impurities which have a dissolution potential comparable to copper, such as arsenic, antimony, and bismuth, behave in a different way. Depending on anode composition and other operational parameters they either report to the slime or to the electrolyte with a widely fluctuating distribution pattern. Further, these elements can, depending on the respective concentration in the electrolyte, undergo several side reactions in the bulk of the electrolyte, resulting in a wide range of insoluble compounds and floating slimes.

Table C-21. Partition Fractions of Impurities in the Electrorefining of Copper

Element	Metal	Anode Slimes	Electrolyte Bleed
Ag	0.04	0.96	
Am			1.0
Ca		0.5	0.5
Co	0.01		0.99
Cs			1.0
Fe	0.02	0.36	0.62
Mn	0.02	0.36	0.62
Ni	0.01		0.99
Np			1.0
Pb	0.003	0.997	
Pu			1.0
Ru	0.03/0.04	0.65/0.70	0.20/0.30
Sb	0.01		0.99
Si		1.0	
Sn	0.001	0.999	
Sr		0.5	0.5
Tc			1.0
Th			1.0
U			1.0
Zn			1.0

Electrode potentials for half-cells of various elements less noble than copper are listed in Table C-22. From this tabulation, it can be deduced that all the listed elements should report to the electrolyte and that a fraction should be continuously removed from the electrorefining circuit with the electrolyte bleed. In the absence of modifying information, all the elements less noble than copper are assumed to report 100% to the electrolyte. During treatment of the electrolyte

bleed, it is not known whether many of these elements would concentrate in the black acid or in the crystallized nickel sulphate. Based on its electrode potential, strontium is expected to concentrate in the electrolyte. However, as noted by Brunson and Stone (1975), some calcium (and, by chemical analogy, strontium) is found in the slimes. Since the calcium content of the anodes is not reported by these authors, a partition ratio cannot be calculated. For Table C-21 it was arbitrarily assumed that calcium (and strontium) is distributed equally between the electrolyte and the slimes. Most of the nickel and probably the zinc, iron, cobalt, and manganese would be recovered from the electrolyte bleed as mixed sulfate crystals<sup>13</sup>.

Table C-22. Half-cell Electrode Potentials of Elements less Noble than Copper

Reaction	Potential (V)
$\text{Cs} = \text{Cs}^+ + \text{e}^-$	-2.92
$\text{Sr} = \text{Sr}^{2+} + 2\text{e}^-$	-2.89
$\text{Am} = \text{Am}^{3+} + 3\text{e}^-$	-2.32
$\text{Pu} = \text{Pu}^{3+} + 3\text{e}^-$	-2.07
$\text{Th} = \text{Th}^{4+} + 4\text{e}^-$	-1.90
$\text{Np} = \text{Np}^{3+} + 3\text{e}^-$	-1.86
$\text{U} = \text{U}^{3+} + 3\text{e}^-$	-1.80
$\text{Zn} = \text{Zn}^{2+} + 2\text{e}^-$	-0.763
$\text{Tc} = \text{Tc}^{\text{x}+} + \text{x}\text{e}^-$	-0.71
$\text{Fe} = \text{Fe}^{2+} + 2\text{e}^-$	-0.44
$\text{Co} = \text{Co}^{2+} + 2\text{e}^-$	-0.277
$\text{Ni} = \text{Ni}^{2+} + 2\text{e}^-$	-0.25
$\text{Cu} = \text{Cu}^{2+} + 2\text{e}^-$	0.337

Sources: Lewis and Randall 1961, Snyder et al. 1987. (All values quoted by Snyder et al. (1987), except the one for Tc, were taken from Latimer 1953.)

Note: Potentials at 25°C

For copper wire and other electrical conductors produced from fire-refined copper, estimating the partition fractions of contaminants in the metal involves combining the factors in Tables C-19 and C-21. Thus, if there were 1 kg of lead in a unit of copper scrap, there would be 220 g of lead in the fire-refined copper and 0.7 g in the electrolytic copper.

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<sup>13</sup> Dobner (1997) has indicated that the composition of crude nickel sulfate ( $\text{NiSO}_4 \cdot 2\text{H}_2\text{O}$ ) is 27% Ni, 0.7% Zn, 0.3% Fe, 0.18% As, and 0.12% Sb.

#### C.4.2 Partitioning During Brass Smelting

Partitioning of contaminants during brass smelting is expected to be different from that in fire refining of copper. In fire-refining operations, the objective is to remove, by oxidation and slagging, as many impurities as possible. In brass melting, on the other hand, one objective is to minimize losses of alloying elements such as Zn, Fe, Mn, Pb, Al, and Sn. Consequently, from a conservative perspective in assessing radiation exposures to radioactive contaminants in metal, it should be assumed that all the contaminants remain in the metal.

### C.5 EXPOSURE SCENARIOS

#### C.5.1 Modeling Parameters

As discussed in the previous sections, there are numerous options for the introduction of copper scrap into the copper refining process. Worker exposures to the contaminated scrap prior to smelting would be relatively independent of where the scrap is introduced into the secondary recovery process but would vary with the type of scrap. Typical operations may involve sorting, shredding, briquetting, and transportation. Insulation removal is required for the recycling of most copper wire.

It is likely that slag generated at any step in the process will be returned to a blast furnace for further processing and only blast furnace (or cleaned blast furnace) slag will exit the process. This slag will be sold or disposed of. The blast furnace operation may be at a different location than the initial secondary smelting operation. In that case, haulage of contaminated slag may be required. Since slag volumes will be smallest when introducing No. 1 copper scrap directly into a fire-refining furnace, the concentrations of any radionuclides that partition to the slag will be greatest for that type of operation. This slag will be diluted when reprocessed in a blast furnace.

Scrap copper released from nuclear installations is likely to be carefully sorted high-quality material. As such, it would most likely be introduced into the secondary refining process at the fire refining stage where it would be used to produce anodes for electrorefining or finished mill products such as sheet and tubing. Expected partitioning of contaminants during fire refining is summarized in Table C-19. While additional partitioning occurs during electrorefining, the result of that process is to further reduce the impurities in the metal. Therefore, it is unlikely that electrorefining of cleared scrap would lead to higher radiation exposures than received during the

fire-refining of such scrap. Possible exceptions could be exposures to anode slimes and electrolyte bleed streams from the electrolysis cells.

#### C.5.1.1 Dilution of Cleared Scrap

The information presented in Section C.1.1 indicates that a maximum of 10,833 t of copper scrap would be cleared in any one year. This represents about 0.8% of the total annual consumption of copper scrap, as listed in Table C-4. Thus, if this scrap were uniformly distributed amongst all consumers, the dilution factor would be 0.008. If all this scrap was processed through a single 200-ton reverberatory furnace, which has an annual capacity of 45,500 tons (~41,300 t) the dilution factor would be 0.26. This calculation assumes that the furnace operates 330 days per year on a 24-hour cycle with 25% of the charge left in the furnace to facilitate the subsequent melting cycle. A more reasonable assumption is that the reference facility—the 200-ton reverberatory furnace cited above—would process the 2,080 t/a of copper scrap generated during the decommissioning of the K-25 Plant at Oak Ridge, while the scrap stockpiled during the years when no scrap was cleared by DOE would have a different disposition. In such a case, the dilution would be 0.05.

#### C.5.1.2 Slag Production

Slag production in a reverberatory furnace varies as a function of the percentage of copper in the charge. With increasing copper grade (Biswas and Davenport 1976):

- Copper concentration in slag increases
- Slag weight decreases
- Copper loss decreases

High-copper-content scrap metal, ranging from 85-95% copper, loaded in a 350-ton-per-day reverberatory furnace, may generate about 30 tons per day of slag. The slag contains an economically recoverable concentration of copper, which may be recycled to a blast furnace for recovery (Murrell 1997). Slag is used for the manufacture of abrasives, shingles, road surface bedding, mineral wool, and cement/concrete materials (Carey 1997).

Slags from a Peirce-Smith converter have an economically viable copper content and may be recycled to a reverberatory or blast furnace to reduce copper loss (Biswas and Davenport 1976).

The process options are myriad; each processor has its own preferred operational cycle. These range from simple remelting and casting, to smelting and recycling the slag, depending upon the available options (Murrah 1997).

One producer, who uses a reverberatory furnace to melt high grade copper scrap and cast logs from which extrusion billets are cut, estimates that the slag weight is about 2 to 2.5% of the charge weight (Burg 1999).

Based on the available information, it is proposed for modeling purposes that a reverberatory furnace melting and fire refining No. 1 copper scrap generates 0.02 tons of slag per ton of scrap charged. Since many oxidizable impurities concentrate in the slag, a small slag volume will increase concentrations of these elements in the slag.

#### C.5.1.3 Baghouse Dusts

In the copper conversion process, baghouse filtration is used at various processing stages to collect zinc, tin and lead dusts. The composition of the dust is a function of the copper charge composition. Thus, dust capture will vary strongly with alloy composition. Assuming a typical converter charge, about 0.25% of the copper in the feed will enter the baghouse collection system as oxide. Dust, depending on the alloy composition of the charge, is sent to lead, zinc, or tin smelters to recover these metals (Edelstein 1997).

In a reverberatory furnace, the dust produced may be as much as 1% of the charge. The dust is frequently recycled to the furnace if the copper content is significant. Dust from a Peirce-Smith converter may contain as much as 11% copper; it is almost always recycled to a smelting furnace (Biswas and Davenport 1976). The mass of dust generated by an EAF used for copper smelting is about 0.25% of the mass of scrap metal charged to the furnace.

However, as noted previously, some operations do not use a baghouse for dust control, so that the species that accumulate in the offgas, as noted in Table C-19, would be released to the atmosphere.

#### C.5.1.4 Electrolyte Bleed

During the final electrolytic purification of copper, part of the electrolyte is bled off to control impurity build-up in the electrolytic cells. The soluble impurities include As, Bi, Co, Fe, Ni, Sb, and Zn. As noted in Section C.4.1.3, As, Bi, and Sb may report either to the electrolyte or to the anode slimes depending on such factors as anode chemistry and cell operating parameters. Actinide elements are also assumed to report to the electrolyte. Some of these impurities are removed from the bleed stream by evaporation and crystallization and may be contained in products which are sold. Other impurities may remain in the electrolyte and be returned to the electrorefining process or used to leach slimes.

The implication is that this added step in the processing of copper creates the potential for a new source of exposure by reconcentrating residual metals. However, most of the residual radioactive contaminants in the cleared copper scrap will have partitioned to the slag or been removed in the offgas well before this stage. The principal exceptions are isotopes of Co, Fe, Ni, Ru, and Zn. If a large electrolytic refinery uses 460,000 tpy of copper anodes containing 0.1% Ni, the nickel content in the feed is 460 tons. According to Table C-21, 99% of Ni is concentrated in the electrolyte bleed stream. If this nickel is crystallized as  $\text{NiSO}_4$ , which is 38% Ni by weight, and if the crude nickel sulfate contains 5%  $\text{H}_2\text{SO}_4$  and 3% water, then the annual production of the crude precipitate is about 1,300 tons ( $460 \times 0.99 \div [0.92 \times 0.38] \approx 1,300$ ). The concentration of nickel in the crude nickel sulfate is 35% ( $0.38 \times 0.92 = 0.35$ ), or about 350 times that of the nickel in the anodes. By chemical analogy, cobalt should be similarly concentrated. While the behavior of other impurities in the electrolyte bleed is unknown, it is likely that some of these will be crystallized with the nickel sulfate.

According to Garbay and Chapuis (1991), a 50,000-t French electrorefining plant produces about 500 t of residual sulfuric acid, about 30 t of arsenical sludge, and about 60 t of nickel sulfate. The nickel sulfate production rate quoted by Garbay and Chapuis—1.2 kg/t of Cu—is lower than that described in the previous paragraph—equivalent to 2.9 kg/t of Cu—partly because the nickel content in the French anodes is only 0.05% (see Section C.2.3.3).

#### C.5.1.5 Anode Slimes

Brunson and Stone (1975) cite a slimes generation rate of 15 lb of anode slimes produced per ton of copper refined at the Southwire Co. This rate of slimes production—7.5 kg/t of Cu—is more than an order of magnitude higher than the 600 g/t quoted by Garbay and Chapuis (1991). The

cause of this difference is not known. However, data quoted by Schloen (1987) corresponds to slimes generation rates ranging from 1 to 7.3 kg/t of anodes for nine U.S. electrolytic refineries, suggesting that the higher figure is more typical of U.S. experience.

#### C.5.1.6 Summary Model for Fire-Refined Products

Based on the information presented above, the following model is proposed for fire-refined products, such as copper tubing.

A 200-ton reverberatory furnace is used to melt No. 1 copper scrap. The furnace operates 12 out of every 14 days, with two days down for routine maintenance. The furnace also is shut down for an additional two weeks per year for major maintenance. The furnace operates on a 24-hour cycle with the following cycle elements :

- Charging ..... 4.5 hr
- Melting ..... 4.5 hr
- Refining and slagging ..... 5.5 hr
- Poling ..... 2.5 hr
- Casting ..... 7 hr

Since about 25% of the melt remains in the furnace as a heel for the subsequent heat, the daily output is 150 tons and the annual output is 45,000 tons. The annual furnace input is 45,500 tons of copper scrap. The furnace produces 910 tons of slag and 110 tons of dust (dust generation of about 5 lb per ton) annually. The slag contains about 40% copper and the dust contains about 75% copper. The dust is either collected in the baghouse or released to the atmosphere. The slag and the dust (if captured) are sent to an outside processor for recovery of additional metal values. Elemental partitioning is presented in Table C-19. The approximate material balance is illustrated in Figure C-4.

The slag from the reverberatory furnace is shipped to an outside processor who treats the material in a 50 tph blast furnace with an annual capacity of 36,000 tons (50 tph  $\times$  24 hr/day  $\times$  300 days/year = 36,000 tons). Thus, the slag from the reverberatory furnace undergoes a further dilution of 0.025 (910  $\div$  36,000  $\approx$  0.025). The blast furnace slag is then sold for industrial applications such as use in abrasives, roofing materials, or road building materials.

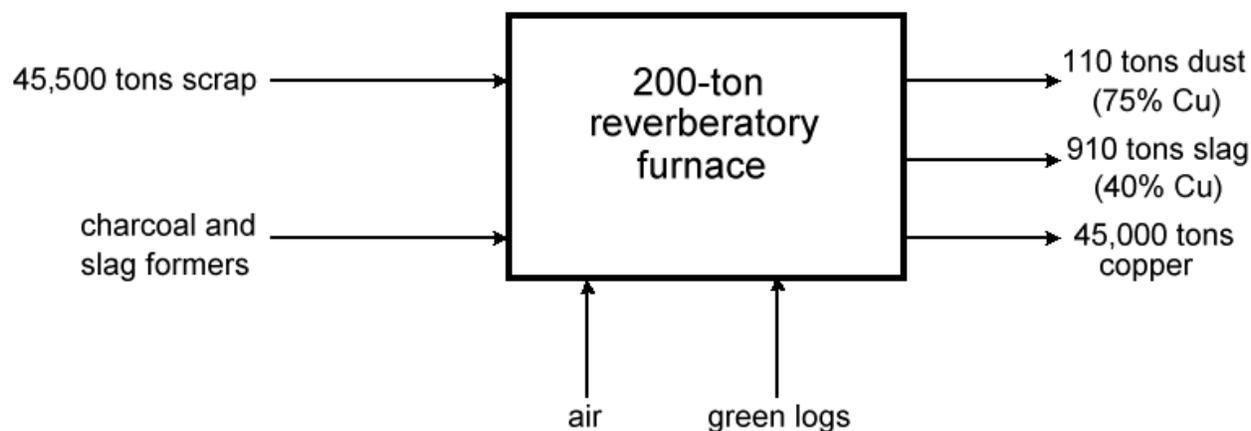


Figure C-4. Proposed Material Balance for Modeling Copper Produced by Fire Refining (values are rounded)

#### C.5.1.7 Summary Model for Electrorefining

Based on the previously presented information, the following model is proposed for high conductivity electrical products, such as wire and cable, which require electrorefining after fire refining for further impurity removal.

Annual output from the electrolytic refinery is 450,000 tons of copper, 3,200 tons of anode slimes, and 1,300 tons of crude nickel sulfate (Schloen 1987). Sulfuric acid recovered from the electrolyte bleed circuit is assumed to be used for electrolyte makeup; accordingly, it is returned to the process. The nickel sulfate, containing 5%  $H_2SO_4$  and 3%  $H_2O$ , is sold to nickel producers for metal recovery. The nickel sulfate also contains contaminants, such as iron and zinc.

The annual input to the reverberatory furnace at the electrorefinery is assumed to be 24,000 tons of No. 2 copper scrap and 102,000 tons of blister copper from primary producers. The average nickel content of the anodes is 0.1%.

An approximate material balance is presented in Figure C-5. Elemental partitioning can be calculated by combining the factors included in Tables C-19 and C-21.

#### C.5.2 Worker Exposures

Dust sampling at a primary copper smelter has been reported by Michaud et al. (1996). Samples were taken at a smelting furnace and a converter located in separate buildings. Results are

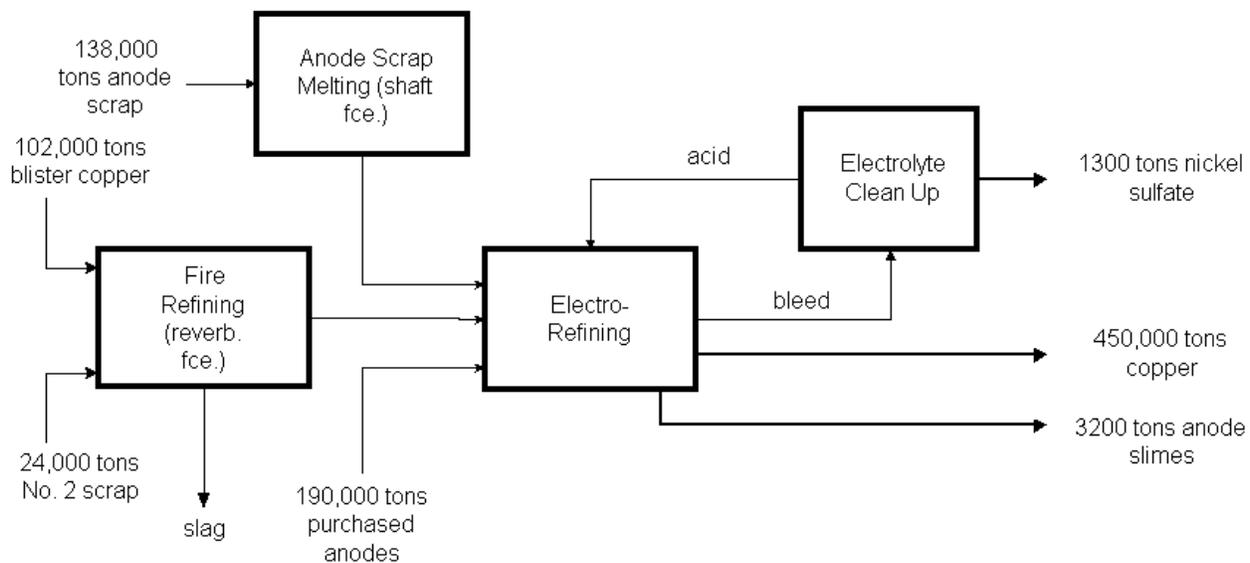


Figure C-5. Simplified Material Balance for Electrorefining of Copper Produced from Scrap

summarized in Table C-23. Cadmium and nickel were not detected in the dusts.

Table C-23. Airborne Dust Concentrations At Primary Copper Smelter (mg/m<sup>3</sup>)

Unit	Total	Respirable	Lead	Copper	Arsenic
Smelting Furnace	2.3	0.6	0.21	0.10	0.02
Converter	2.1	0.8	0.15	0.32	0.02

Source: Michaud et al. 1996

### C.5.2.1 Baghouse Dust Agglomeration Operator

As noted in Table C-19, cesium is the main contaminant that would distribute to the offgas during fire refining of copper scrap. The exposure scenario developed here is designed to capture worker exposure to this dust and is based primarily on information presented in Section C.2.3.8.

Basic assumptions include:

- Copper output ..... 342,000 tpy
- Baghouse dust from fire-refining furnaces ..... 51,100 tpy
- Cesium partitioning to dust ..... 90%

Based on these assumptions, the dust generation rate will be 0.15 tons of dust per ton of copper product ( $51,100 \div 342,000$ ). The cesium reconcentration factor due to preferential partitioning to the dust will be 6:1 ( $5,000 \times 0.9 \div 750$ ). The operator would be exposed for 7 hours per day, 5 days per week to the mass of wetted dust in a concrete bunker that is about  $20 \times 30 \times 12$  ft high. It is assumed that the bunker contains a maximum of three days' output from the agglomerator or 420 tons ( $20 \text{ tph} \times 7 \text{ hr/d} \times 3 \text{ d} = 420 \text{ tons}$ ).

If the recycling facility used a reverberatory furnace without a baghouse, then all the cesium would be exhausted up the stack and become airborne.

#### C.5.2.2 Furnace Operator

A furnace operator would be part of a crew that spends full time in the vicinity of the reverberatory furnace that holds 200 tons of copper. For about two hours per shift, he would be standing 5 to 10 ft from an open furnace, skimming slag from the furnace with a rake into a metal box about  $4 \times 4 \times 1$  ft. Another operator would transport the slag box with a forklift truck about 200 ft to an area on the furnace room floor where the box is dumped. The cooled slag is broken up by an operator with a pneumatic hammer; copper is then culled by hand from the slag. At other times the operator will be shoveling charcoal and slag-forming agents into the furnace or tapping the furnace to allow the molten metal to flow through launders to the holding furnace.

#### C.5.2.3 Scrap Handler

The scrap handler would spend full time in the vicinity of the scrap piles preparing the material for charging into the furnace. This might include loading material into a briquetting machine and transporting the briquetted scrap to a staging area with a fork-lift truck. On average, about 200 tons of scrap are stockpiled in the scrap-handling area.

#### C.5.2.4 Casting Machine Operator

A casting machine operator would cast the copper into logs and assist in moving the cooled logs from the casting machine cooling pit to the billet-cutting machine. The operator would spend full time working near several copper logs that are about 26 feet long and up to 12 inches in diameter.

### C.5.2.5 Scrap Metal Transporter

If all the scrap from the largest annual DOE source (i.e. 2,080 t from the K-25 plant in Oak Ridge) were shipped to Southwire in Carrollton, Ga. for recycling, 104 shipments in a 20-t truck would be required. The distance is about 250 miles; the estimated driving time is six hours. Thus the total driver exposure would be about 624 hours. Other situations, which would lead to greater exposures, are possible. To accommodate this possibility, it is conservatively assumed that a truck driver spends full time driving a 20-t truck, with the truck loaded only one-half of the time (i.e., about 1,000 hr/y).

### C.5.2.6 Tank House Operator

A tank house operator in a 450,000 tpy electrolytic refining plant would collect and drum 3,200 tons of anode slimes for transport to a refinery for metals recovery.

## C.5.3 Non-Industrial Exposures

### C.5.3.1 Driver of Motor Vehicle

The average amount of copper used in automobiles or light trucks is 50 pounds. The radiator contains about 80% of this; the electrical system contains about 20%. These elements are mostly under the hood presenting minimal exposure hazards. The radiator would consist of recycled scrap (CDA 1997). It is likely that the copper would come from several lots of material with differing processing histories.

### C.5.3.2 Homemaker

Home appliances and heating and cooling systems contain copper produced from recycled scrap. Copper usage in home appliances is as follows (CDA 1997):

- Central Air Conditioner ..... 50 lb
- Refrigerator ..... 5 lb
- Dishwasher ..... 5 lb
- Washing Machine ..... 4.4 lb
- Dryer ..... 2 lb
- Range ..... 1.3 lb

- Garbage Disposer ..... 2.3 lb
- Dehumidifier ..... 2.7 lb
- Heat Pump ..... 48 lb

Radiation exposures from any residual radioactive contaminants in these products would be very low relative to those associated with handling copper scrap and finished and semi-finished products made from this metal during the various stages in the copper refining process. This is primarily because of the small quantities of copper in these products, and because the copper would be obtained from many different lots of material, not all of which would be produced from cleared scrap.

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**APPENDIX C-1**

**PARTITIONING DURING FIRE REFINING AND ELECTROREFINING  
OF COPPER SCRAP**

Table C1-1. Partitioning During Fire Refining and Electrolysis of Copper Scrap

Reverb charge	45500 tons															
Reverb output	910 tons in slag		910 tons at 40% Cu													
	110 tons in dust		110 tons at 75% Cu													
	45000 tons in anode Cu															
Electrolytic Cell output	44500 tons as cathodes															
	337.5 tons as slimes		15 lb/ton													
	128.7 tons as nickel sulfate (38%Ni)															
													Adjusted	Adjusted	Adjusted	
	Anodes		Cathodes		Metal	Slimes	Slimes	Slimes	Bleed	Bleed	Material Balance		Slimes	Bleed	Metal	Partition
	(wt. %)	tons	(ppm)**	tons	Partition	(wt %)	tons	Partition	tons	Partition	tons unaccounted		Partition	Partition	Partition	Check
Cu	99.5	44775	99.99%	44495.55		8.77	29.60									
Ni	0.1	45	7	0.31	0.0069	0	0.00	0.000	44.69	0.99	0.00		0.000	0.993	0.0069	1.0000
Sb	0.01	4.5	1	0.04	0.0099	0	0.00	0.000			4.46	add bal. to bleed	0.000	0.990	0.0099	1.0000
Sn	0.025	11.25	1	0.04	0.0040	9.28	31.32	2.784			-20.11	add bal. to anodes	0.999	0.000	0.0014	1.0000
Fe	0.025	11.25	6	0.27	0.0237	1.2	4.05	0.360			6.93	add bal. to bleed	0.360	0.616	0.0237	1.0000
Zn	0.013	5.85	0	0.00	0.0000	0	0.00	0.000			5.85	add bal. to bleed	0.000	1.000	0.0000	1.0000
Pb	0.19	85.5	5	0.22	0.0026	31.45	106.14	1.241			-20.87	subt. bal. fr. slimes	0.997	0.000	0.0026	1.0000
Ag	0.024	10.8	10	0.45	0.0412	5.2	17.55	1.625			-7.20	subt. bal. fr. slimes	0.959	0.000	0.0412	1.0000
Bi	0.0007	0.315	0.1	0.00	0.0141	0	0.00	0.000			0.31	add bal. to bleed	0.000	0.986	0.0141	1.0000
As	0.005	2.25	1	0.04	0.0198	0.75	2.53	1.125			-0.33	subt. bal. fr. slimes	0.980	0.000	0.0198	1.0000
Te	0.0003	0.135	1	0.04	0.3296	0	0.00	0.000			0.09	add bal. to slimes	0.670	0.000	0.3296	1.0000
Se	0.031	13.95	0.5	0.02	0.0016	0	0.00	0.000			13.93	add bal. to slimes	0.998	0.000	0.0016	1.0000
Ca						1.1	3.71	0.500*			-3.71	add bal. to anodes	0.500	0.500	0.0000	1.0000
Si						3.5	11.81	1.000*			-11.81	add bal. to anodes	1.000	0.000	0.0000	1.0000
Total		44965.8		44497			194.91				-32.46					
			**unless other units shown													
						140 tons of slimes not accounted for										

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## **APPENDIX D**

### **SELECTION OF RADIONUCLIDES FOR RADIOLOGICAL ASSESSMENT**

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## SELECTION OF RADIONUCLIDES FOR RADIOLOGICAL ASSESSMENT

### D.1 SOURCES USED TO MAKE RECOMMENDATIONS

The following sources were reviewed and used to arrive at the recommendations as to which long-lived (i.e., half-lives greater than six months) radionuclides should be included in the present analysis. The nuclides selected from each source and considered as candidates for the analysis are listed in Table D-6. Each source is referred to by a mnemonic or a short title, which in most cases is the document number.

#### D.1.1 IAEA-TECDOC-855

Table I of “Clearance Levels for Radionuclides in Solid Materials: Application of Exemption Principles” (IAEA 1996) presents clearance levels—expressed in units of Bq/g—for the unconditional release of material with radioactive contamination. To determine these levels, the IAEA reviewed a large number of documents. The following four documents are relevant to the release of metals (including steel, aluminum, and copper): “Principles for the Exemption of Radiation Sources and Practices from Regulatory Control,” Safety Series No. 89 (IAEA 1988); “Radiological Protection Criteria for the Recycling of Materials from Dismantling of Nuclear Installations,” Radiation Protection No. 43 (CEC 1988); “Basis for Criteria for Exemption of Decommissioning Waste” (Elert et al. 1992); and “Radiological Impacts of Very Slightly Radioactive Copper and Aluminium Recovered from Dismantled Nuclear Facilities” (Garbay and Chapuis 1991). The radionuclides that were included in the radiological assessments of clearance (along with their respective release limits) in each of these four documents are listed in Table I.3 of IAEA 1996. Only those nuclides that are associated with clearance of metals are considered as candidates for the present analysis.

#### D.1.2 NUREG/CR-0134

In “Potential Radiation Dose to Man from Recycle of Metals Reclaimed from a Decommissioned Nuclear Power Plant,” NUREG/CR-0134 (O’Donnell et al. 1978), the authors present individual and population dose factors resulting from scrap metal recycle for 27 radionuclides. These nuclides “... include fission and activation products (except gaseous species) that may be encountered during decommissioning, and that have radioactive half-lives longer than about 40 days, <sup>239</sup>Pu and <sup>241</sup>Am (to characterize transuranic contaminants), and <sup>234</sup>U, <sup>235</sup>U, and <sup>238</sup>U.”

### D.1.3 WINCO-1191

The radionuclides reported in “Radionuclides in the United States Commercial Nuclear Power Reactors,” WINCO-1191 (Dyer 1994) were taken from a study of pipe samples and pipe surface contamination from pressurized and boiling water reactors; they are listed in Table D-1. The samples were from 11 pressurized water reactors (PWRs) and "over" eight boiling water reactors (BWRs). The data were based on surface samples taken from the inside of stainless steel piping, a main coolant system check valve, and from fuel element hardware. The study also includes an analysis of the Shippingport reactor material samples. Radionuclides that are found exclusively in the coolant or within the fuel cladding are not considered to be candidates for inclusion in the present analysis.

The study notes that between 86% and 99% of the activities from the pipe walls and pipe surfaces are the activation products Fe-55, Co-60, and Ni-63. The author goes on to note that the distribution of radionuclides in reactor component appears to be the same whether the activities are on surfaces or are within the metal.

### D.1.4 NUREG/CR-0130

Appendix J of “Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station,” NUREG/CR-0130 (Smith et al. 1978) presents five sets of “reference radionuclide inventories” that were used to characterize a PWR at the time of its decommissioning. Four of the reference inventories are associated with contaminated metal components, and are listed in Table D-2, while the fifth set is for contaminated concrete, and is not relevant to the present study.

The metals removed during PWR decommissioning which are contaminated with either activated corrosion products or surface contamination would be candidates for recycling. The authors include the “stainless and carbon steel activation products” classes of radionuclides, which are the contaminants on the reactor vessel and its internals. In a PWR at the time of decommissioning, this metal would be too highly activated to be a candidate for recycling. However, stainless and carbon steel can become activated by other means, or a reactor may have operated for only a short time (e.g., Shoreham), therefore, the radionuclides in these two sets are candidates for inclusion in the present analysis.

Table D-1. Nuclides from WINCO-1191

Nuclide	Half-Life (y)	Surface Activity at Shutdown ( $\mu\text{Ci}/\text{cm}^2$ )
C-14 <sup>a</sup>	5.73e+03	< 5.9e-08
Mn-54 <sup>a</sup>	8.55e-01	6.9e-03
Fe-55 <sup>a</sup>	2.73e+00	2.7
Co-57 <sup>b</sup>	7.44e-01	1.78e-05
Ni-59 <sup>a</sup>	7.60e+04	6.80e-03
Co-60 <sup>a</sup>	5.27e+00	2.0
Ni-63 <sup>a</sup>	1.00e+02	1.55
Zn-65 <sup>b</sup>	6.69e-01	1.68e-06
Nb-93m <sup>a</sup>	1.46e+01	1.2e-02
Nb-94 <sup>a</sup>	2.03e+04	8.4e-05
Ag-110m <sup>b</sup>	6.84e-01	1.3e-04
Mo-93 <sup>c</sup>	3.50e+03	1.8e-08 <sup>d</sup>
Sb-125 <sup>c</sup>	2.76e+00	1.0e-05 <sup>d</sup>
I-129 <sup>a</sup>	1.57e+07	<1.6e-08
Ce-144+D <sup>b</sup>	7.81e-01	2.49E-6
Pu-238 <sup>a</sup>	8.77e+01	1.2e-07
Pu-239/240 <sup>a</sup>	2.41e4/6.56e3	4.7e-08
Cm-244 <sup>a</sup>	1.81e+01	2.6e-08

- a Sample taken from Shippingport B-loop Primary Coolant Check Valve. Total activity in sample: 6.27  $\mu\text{Ci}/\text{cm}^2$ .
- b Sample taken from Ranch Seco Nuclear Power Plant. Total activity in sample: 0.252  $\mu\text{Ci}/\text{cm}^2$ .
- c Sample taken from Shippingport reactor internals. Total activity in sample: 3.85E-3  $\mu\text{Ci}/\text{g}$ .
- d Specific activity ( $\mu\text{Ci}/\text{g}$ )

Konzek et al. (1995) revised the PWR decommissioning analysis originally presented by Smith et al. (1978) to reflect current regulations, practices and costs. The authors did not re-analyze the radiological source terms presented in Appendix C by Smith et al. (1978), although they did use “as built” drawings, rather than design drawings, for estimating the volume of waste material and equipment (Bierschbach 1996). This could change the radionuclide inventories but would not result in any major changes to the expected radionuclide distributions in PWR components at the time of decommissioning.

Table D-2. Nuclides Included in NUREG/CR-0130

Nuclide	Stainless Steel AP <sup>a</sup>	Carbon Steel AP	Activated Corrosion Products	Surface Contamination
Mn-54	✓ <sup>b</sup>	✓	✓	✓
Fe-55	✓	✓	--	✓
Co-60	✓	✓	✓	✓
Ni-59	✓	✓	--	--
Ni-63	✓	✓	--	--
Zn-65	✓	--	--	--
Sr-90	--	--	--	✓
Mo-93	✓	✓	--	--
Nb-94	✓	--	--	--
Ru-106	--	--	✓	--
Cs-134	--	--	--	✓
Cs-137	--	--	✓	✓

<sup>a</sup> AP = activation product

<sup>b</sup> A check mark (✓) indicates that the radionuclide is included in the NUREG/CR-0130 reference inventory.

#### D.1.5 NUREG/CR-3585

In “De Minimis Impacts Analysis Methodology,” NUREG/CR-3585, (Oztunali and Roles 1984), the authors present an analysis of the impacts of clearance of metals. Any metal which met the *de minimis* activity level would have been considered to be a candidate for clearance, since it would no longer have been under regulatory control.

#### D.1.6 NUREG/CR-4370

“Update of Part 61 Impacts Analysis Methodology,” NUREG/CR-4370 (Oztunali and Roles 1986) was reviewed as a source of information concerning the radiological profile of scrap which would be disposed of as low-level waste—cleared scrap would have a similar profile. The report analyzed 53 radionuclides, increased from the 23 analyzed in the original Part 61 analysis methodology. Table D-3 list these 53 nuclides.

Oztunali and Roles (1986) identified 148 waste streams, for which they developed radionuclide characterizations. Only three of the 148 streams are directly applicable to the recycling of scrap:

1. The nuclear power plant decommissioning contaminated metals
2. The West Valley Demonstration Project equipment and hardware
3. Non-compressible trash

Table D-3. Nuclides Analyzed in NUREG/CR-4370

Nuclide	Notes	Nuclide	Notes	Nuclide	Notes
H-3	a, b, c	Cs-135	a, b, c	U-236	c
C-14	a, b, c	Cs-137	a, b, c	U-238	a, c
Na-22	NI	Eu-152	b	Np-237	a, b, c
Cl-36	--	Eu-154	b	Pu-236	c
Fe-55	a, c	Pb-210	NI	Pu-238	a, b, c
Co-60	a, c	Ac-227	HLW	Pu-239	a, b, c
Ni-59	a, c	Th-228	--	Pu-240	a, c
Ni-63	a, b, c	Th-229	NI	Pu-241	a, b, c
Sr-90	a, b, c	Rn-222	NI	Pu-242	a, b, c
Nb-94	a, c	Ra-226	--	Pu-244	NI
Tc-99	a, b, c	Ra-228	NI	Am-241	a, b, c
Ru-106	b	Th-230	HLW	Am-243	a, b, c
Ag-108m	NI	Th-232	NI	Cm-242	b, c
Cd-109	NI	Pa-231	HLW	Cm-243	a, b, c
Sn-126	b	U-232	HLW	Cm-244	a, b, c
Sb-125	b	U-233	--	Cm-248	HLW
I-129	a, b, c	U-234	c	Cf-252	HLW
Cs-134	b	U-235	a, c		

- a Associated with the nuclear-power-plant-decommissioning contaminated metals waste streams
- b Associated with the West Valley Demonstration Project equipment and hardware waste streams
- c Associated with non-compressible trash waste streams
- NI Nuclide was not included in the characterization of any of the waste streams in NUREG/CR-4370, may be included as a decay product of another nuclide which is included in the waste stream characterization.
- HLW Nuclide was only included in the spent fuel reprocessing high-level liquid waste stream.

#### D.1.7 SAND92-0700

In volume 3 of the “Preliminary Performance Assessment for the Waste Isolation Pilot Plant,” SAND92-0700/3, Peterson (1992) estimates the radionuclide inventories in DOE-generated

transuranic (TRU) waste that would be disposed of at the Waste Isolation Pilot Project (WIPP). Because the radionuclides present in TRU waste are a likely source of the contamination of metals present at DOE facilities, Peterson's memo is included in the present review. The memo classified TRU waste as to whether it can be contact handled (CH) or whether remote handling (RH) is required. Both types of TRU waste are considered for the scrap recycle analysis—Table D-4 indicates the type of TRU waste in which the radionuclide may be found.

Table D-4. Nuclides Analyzed by SAND92-0700 for WIPP

Nuclide	Half-Life (y)	RH <sup>a</sup>	CH <sup>b</sup>	Nuclide	Half-Life (y)	RH <sup>a</sup>	CH <sup>b</sup>
Mn-54	8.56e-01	✓	—	Th-232	1.41e+10	✓	✓
Co-60	5.27e+00	✓	—	U-233	1.59e+05	✓	✓
Ni-63	1.00e+02	✓	—	U-235	7.05e+08	✓	✓
Sr-90	2.91e+01	✓	✓	U-236	2.34e+07	✓	—
Tc-99	2.13e+05	✓	—	U-238	4.47e+09	✓	✓
Ru-106	1.01e+00	✓	✓	Np-237	2.14e+07	✓	✓
Sb-125	2.77e+00	✓	—	Pu-238	8.77e+01	✓	✓
Cs-134	2.06e+00	✓	—	Pu-239	2.41e+04	✓	✓
Cs-137	3.00e+01	✓	✓	Pu-240	6.56e+03	✓	✓
Ce-144	7.78e-01	✓	✓	Pu-241	1.44e+01	✓	✓
Pm-147	2.62e+00	✓	✓	Pu-242	3.75e+05	✓	✓
Eu-152	1.33e+01	✓	—	Am-241	4.33e+02	✓	✓
Eu-154	8.80e+00	✓	—	Cm-244	1.81e+01	✓	✓
Eu-155	4.96e+00	✓	—	Cf-252	2.64e+00	✓	✓

<sup>a</sup> Waste requires remote handling due to high external exposure rate

<sup>b</sup> Waste can be handled by direct contact

### D.1.8 ORIGEN

The Oak Ridge Isotope Generation and depletion code (ORIGEN) (Croff 1980) includes a radionuclide library with approximately 1,700 entries collected into three groups: activation products, transuranics, and fission products. Included are 1,040 individual nuclides (a given nuclide can appear in more than one group), 127 of which have half-lives greater than six months.

To determine which of these 127 radionuclides should be included in the present analysis, an ORIGEN analysis was performed to calculate the activity in spent fuel at the time of discharge from the reactor. An initial enrichment of 3.04% U-235 was assumed, with a burnup of 44,340 MW-days per metric ton of initial heavy metal (MWD/MTIHM), and the characteristics of PWR fuel with impurities. For the purpose of this selection process, it was assumed that the specific activity of a given nuclide in scrap metal from a nuclear facility would be proportional to its activity in the spent fuel inventory. Furthermore, it was assumed that the dose to an exposed individual from a given nuclide, via one of the three pathways (inhalation, ingestion and external exposure) considered in the radiological assessments presented in the main body of this report, would be proportional to the dose conversion factor (DCF) for that pathway. (The DCFs are listed in Federal Guidance Reports (FGR) No. 11 [Eckerman et al. 1988] for internal exposure and No. 12 [Eckerman and Ryman 1993] for external exposure.)<sup>1</sup> We therefore assigned a “significance,” which we define as the product of the activity in spent fuel and the DCF, to each of the 127 nuclides. For each pathway, we found the nuclide with the highest significance. We then calculated the ratio of the significance of each nuclide for each pathway to the significance of the maximum nuclide—the one with the highest significance

$$R_{ij} = \frac{A_i F_{ij}}{A_{m_j} F_{m_jj}}$$

where:

$R_{ij}$  = significance ratio for radionuclide  $i$  and pathway  $j$

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<sup>1</sup> The scoping analysis described in this section was performed in support of the 1997 Draft “Technical Support Document: Evaluation of the Potential for Recycling of Scrap Metals from Nuclear Facilities.” This scoping analysis was but one of nine criteria used in the radionuclide selection process, and contributed at most 2 points out of a possible score of 30. Although the radiological assessments presented in the main body of the present report utilized the revised internal exposure DCFs from ICRP Publication 68 (ICRP 1994), it is unlikely that the selected radionuclides would change if the more current DCFs were used in the selection process.

- $A_i$  = spent fuel activity for radionuclide  $i$
- $F_{ij}$  = dose conversion factor for radionuclide  $i$  in pathway  $j$  (FGR 11 for internal, FGR 12 infinite soil coefficients for external)
- $A_{m_j}$  = spent fuel activity for radionuclide with the maximum significance for pathway  $j$
- $F_{m_jj}$  = DCF for the radionuclide with the maximum significance for pathway  $j$

The results of this scoping analysis are listed in Table D-5.

### D 1.9 SAND91-2795

The “Yucca Mountain Site Characterization Project, TSPA 1991: An Initial Total-System Performance Assessment for Yucca Mountain, SAND91-2795 (Barnard et al. 1992) presents an analysis of the impacts from the disposal of spent fuel. Because the radionuclides present in spent fuel are a likely source for the contamination of metals present in nuclear power plants and other tail-end fuel cycle facilities, this report was included in the present review.

## D.2 RADIONUCLIDES RECOMMENDED FOR INCLUSION

Table D-6 lists all radionuclides with half-lives greater than six months which were included in the present review. A check mark (✓) in the last column of Table D-6 indicates that that radionuclide is recommended for inclusion in the scrap recycle analysis. The basis for these recommendations is discussed below.

### D.2.1 Basis for Recommendations

A recommendation to include a radionuclide in the scrap recycle analysis is based on the following:

- Each of the sources reviewed was assigned a weighting factor, depending on its applicability to scrap recycle. The weighting factors range from 6 for those sources which are most applicable to scrap recycle to 2 for those documents which are least applicable. These weighting factors are shown in parentheses below the designation of each source document in the heading of Table D-6.

Table D-5. Nuclides from ORIGEN with Normalized Activity-Weighted Dose Factors

Nuclide	∞ Soil	Inhalation	Ingestion	Nuclide	∞ Soil	Inhalation	Ingestion
H-3	0.00e+00	3.04e-08	2.31e-06	Rh-102	1.16e-05	1.27e-07	8.42e-07
Be-10	2.96e-15	1.16e-12	1.15e-12	Pd-107	0.00e+00	1.09e-09	9.72e-10
C-14	3.95e-12	7.27e-10	5.51e-08	Ag-108m	6.40e-08	2.23e-09	4.54e-09
Na-22	0.00e+00	0.00e+00	0.00e+00	Ag-110m	6.04e-02	3.35e-04	3.42e-03
Si-32	2.09e-16	2.16e-14	1.74e-14	Cd-109	9.07e-09	8.36e-08	7.29e-07
Cl-36	1.38e-11	1.50e-10	1.57e-09	Cd-113m	2.45e-08	6.86e-05	5.48e-04
Ar-39	3.33e-14	0.00e+00	0.00e+00	In-115	2.30e-21	2.53e-17	8.10e-17
Ar-42	Not in FGR 11 or 12			Sn-119m	4.15e-07	1.02e-06	1.73e-05
K-40	2.73e-15	3.85e-17	4.39e-15	Sn-121m	2.57e-10	1.72e-09	2.47e-08
Ca-41	0.00e+00	1.49e-13	1.07e-11	Sn-126	5.11e-06	5.19e-08	8.19e-07
V-49	0.00e+00	0.00e+00	0.00e+00	Sb-125	1.94e-02	1.31e-04	2.61e-03
V-50	Not in FGR 11 or 12			Te-123	1.20e-20	2.28e-20	6.86e-19
Mn-54	4.64e-06	7.15e-09	2.24e-07	I-129	2.15e-10	3.42e-09	4.13e-07
Fe-55	0.00e+00	1.63e-08	2.79e-07	Cs-134	1.00e+00	5.79e-03	6.96e-01
Co-60	8.77e-04	1.40e-05	1.31e-04	Cs-135	6.88e-12	9.70e-10	1.14e-07
Ni-59	0.00e+00	1.66e-11	9.79e-11	Cs-137	1.81e-01	2.01e-03	2.38e-01
Ni-63	0.00e+00	6.27e-09	4.36e-08	Ba-133	1.75e-36	8.16e-39	2.70e-37
Zn-65	2.44e-04	1.59e-06	8.55e-05	La-137	0.00e+00	0.00e+00	0.00e+00
Se-79	3.75e-12	2.35e-09	1.58e-07	La-138	7.05e-15	1.44e-15	4.69e-16
Kr-81	1.05e-14	0.00e+00	0.00e+00	Ce-142	Not in FGR 11 or 12		
Kr-85	6.17e-05	0.00e+00	0.00e+00	Ce-144	1.71e-01	2.33e-01	1.00e+00
Rb-87	1.37e-15	3.73e-14	4.31e-12	Nd-144	Not in FGR 11 or 12		
Sr-90	8.11e-04	5.09e-02	4.53e-01	Pm-145	0.00e+00	0.00e+00	0.00e+00
Zr-93	0.00e+00	3.24e-07	1.27e-07	Pm-147	2.27e-06	2.11e-03	4.28e-03
Nb-91	Not in FGR 11 or 12			Pm-146	8.39e-06	3.31e-07	6.28e-07
Nb-93m	6.54e-12	2.18e-09	2.95e-09	Sm-145	0.00e+00	0.00e+00	0.00e+00
Nb-94	8.24e-10	4.18e-11	5.47e-11	Sm-146	0.00e+00	1.10e-11	2.05e-12
Mo-93	2.15e-13	1.23e-11	4.42e-11	Sm-147	0.00e+00	4.46e-11	8.40e-12
Tc-97	0.00e+00	0.00e+00	0.00e+00	Sm-148	Not in FGR 11 or 12		
Tc-98	3.48e-11	1.10e-13	1.78e-12	Sm-149	Not in FGR 11 or 12		
Tc-99	7.79e-10	6.13e-08	8.16e-07	Sm-151	1.72e-10	6.23e-06	6.13e-06
Ru-106	4.30e-01	1.88e-01	8.20e-01	Eu-152	1.68e-05	6.26e-07	1.39e-06
Eu-154	5.38e-02	2.37e-03	6.01e-03	U-233	7.03e-15	8.08e-10	1.31e-10

Table D-5 (continued)

Nuclide	∞ Soil	Inhalation	Ingestion	Nuclide	∞ Soil	Inhalation	Ingestion
Eu-155	8.27e-04	2.23e-04	6.24e-04	U-234	1.32e-10	5.17e-05	8.40e-06
Eu-150	7.03e-11	2.56e-12	4.62e-12	U-235	2.89e-09	5.57e-07	9.20e-08
Gd-152	0.00e+00	2.76e-17	1.38e-18	U-236	2.16e-11	1.50e-05	2.43e-06
Gd-153	6.08e-06	7.01e-07	2.62e-06	U-238	1.80e-08	1.67e-05	2.87e-06
Tb-157	0.00e+00	0.00e+00	0.00e+00	Np-235	1.42e-11	2.16e-11	9.59e-11
Ho-163	Not in FGR 11 or 12			Np-236	1.71e-12	4.58e-10	2.89e-10
Ho-166m	3.24e-08	2.88e-09	2.28e-09	Np-237	1.76e-07	1.03e-04	6.40e-05
Tm-171	2.01e-12	1.95e-11	6.96e-11	Pu-236	1.10e-10	8.24e-05	5.04e-05
Lu-176	4.83e-33	1.50e-33	1.26e-33	Pu-238	2.51e-07	7.71e-01	4.77e-01
Hf-182	0.00e+00	0.00e+00	0.00e+00	Pu-239	3.99e-08	6.88e-02	4.30e-02
Ta-180	0.00e+00	0.00e+00	0.00e+00	Pu-240	3.36e-08	1.17e-01	7.30e-02
Re-187	0.00e+00	1.81e-19	2.41e-18	Pu-241	1.35e-06	7.00e-01	4.41e-01
Os-194	5.32e-17	7.74e-17	1.41e-16	Pu-242	1.74e-10	6.63e-04	4.12e-04
Ir-192m	1.84e-14	1.68e-15	2.25e-15	Pu-244	1.38e-12	3.28e-10	2.05e-10
Pt-190	Not in FGR 11 or 12			Am-241	2.83e-06	3.41e-02	2.12e-02
Pt-193	1.73e-19	8.25e-18	3.27e-16	Am-242m	2.73e-07	2.09e-03	1.30e-03
Tl-204	0.00e+00	0.00e+00	0.00e+00	Am-243	1.68e-05	9.82e-03	6.14e-03
Pb-204	Not in FGR 11 or 12			Cm-243	1.14e-05	7.12e-03	4.42e-03
Pb-205	6.92e-21	4.56e-18	1.44e-16	Cm-244	4.28e-07	1.00e+00	6.17e-01
Pb-210	1.39e-17	6.26e-14	1.49e-12	Cm-245	1.22e-07	1.93e-04	1.20e-04
Bi-208	Not in FGR 11 or 12			Cm-246	1.24e-11	5.71e-05	3.55e-05
Bi-210m	1.31e-14	8.51e-14	8.16e-14	Cm-247	8.17e-13	2.16e-10	1.35e-10
Ra-226	7.07e-14	6.43e-14	7.53e-13	Cm-248	1.31e-16	2.92e-09	1.82e-09
Ra-228	5.70e-18	5.73e-18	1.24e-16	Cm-250	4.83e-19	2.83e-15	1.77e-15
Ac-227	3.12e-13	1.24e-09	2.06e-10	Bk-249	4.75e-14	1.16e-08	7.59e-09
Th-228	1.26e-08	5.06e-07	8.98e-08	Cf-249	4.21e-12	1.56e-09	9.69e-10
Th-229	1.46e-13	2.35e-10	3.32e-11	Cf-250	1.27e-14	3.34e-08	2.06e-08
Th-230	9.83e-15	3.14e-09	4.01e-10	Cf-251	3.71e-13	4.91e-10	3.07e-10
Th-232	4.79e-21	1.79e-14	2.26e-15	Cf-252	3.21e-14	3.39e-08	1.78e-08
Pa-231	1.06e-12	8.47e-09	5.30e-09	Es-254	1.11e-12	9.71e-12	5.64e-12
U-232	5.60e-12	4.85e-06	7.31e-07				

- For each radionuclide identified in one or more of the sources reviewed, a score was calculated by summing the weighting factors for each source in which the radionuclide appeared. These scores are shown in the second column from the right (headed “score”) in Table D-6.
- Those radionuclides with a score of 10 or greater are recommended for inclusion in the scrap recycle analysis, as indicated by a check mark in the last column of Table D-6.
- Members of the thorium and uranium radioactive decay series have been recommended for inclusion even if they have scores below 10, to enable the radiological assessment of the entire series in secular equilibrium.

Table D-6. Selection of Nuclides to Be Included in Scrap Recycle Analysis

Nuclide	Source (weighting factor)									Score	Include
	NUREG/ CR-0134	IAEA 1996	WINCO 1191	NUREG/ CR-0130	NUREG/ CR-3585	NUREG/ CR-4370	SAND 92 -0700	ORIGEN	SAND 91-2795		
	(5)	(6)	(4)	(4)	(3)	(2)	(2)	(2)	(2)		
H-3	—	—	—	—	✓	✓	—	—	—	5	—
C-14	✓	—	✓	—	✓	✓	—	—	✓	16	✓
Na-22	✓	—	—	—	✓	—	—	—	—	8	—
Cl-36	—	—	—	—	✓	—	—	—	✓	5	—
Mn-54	✓	✓	✓	✓	✓	—	✓	—	—	24	✓
Fe-55	✓	✓	✓	✓	✓	✓	—	—	—	24	✓
Co-57	—	—	✓	—	✓	—	—	—	—	7	—
Co-60	✓	✓	✓	✓	✓	✓	✓	✓	—	28	✓
Ni-59	✓	—	✓	✓	✓	✓	—	—	✓	20	✓
Ni-63	✓	✓	✓	✓	✓	✓	✓	—	✓	28	✓
Zn-65	✓	✓	✓	✓	✓	—	—	✓	—	24	✓
Se-79	—	—	—	—	—	—	—	—	✓	2	—
Rb-86	—	—	—	—	✓	—	—	—	—	3	—
Sr-90	✓	✓	—	✓	✓	✓	✓	✓	✓	26	✓
Zr-93	—	—	—	—	—	—	—	—	✓	2	—
Nb-93m	—	—	✓	—	—	—	—	—	—	4	—
Nb-94	—	✓	✓	✓	✓	✓	—	—	✓	21	✓
Mo-93	—	—	✓	✓	—	—	—	—	✓	10	✓
Tc-99	✓	✓	—	—	✓	✓	✓	—	✓	20	✓
Ru-106	✓	✓	—	✓	✓	✓	✓	✓	—	24	✓
Pd-107	—	—	—	—	—	—	—	—	✓	2	—

Table D-6 (continued)

Nuclide	Source (weighting factor)									Score	Include
	NUREG/ CR-0134	IAEA 1996	WINCO 1191	NUREG/ CR-0130	NUREG/ CR-3585	NUREG/ CR-4370	SAND 92 -0700	ORIGEN	SAND 91-2795		
	(5)	(6)	(4)	(4)	(3)	(2)	(2)	(2)	(2)		
Ag-108m	—	—	—	—	✓	—	—	—	✓	5	—
Ag-110m	—	✓	✓	—	✓	—	—	✓	—	15	✓
Cd-109	—	—	—	—	✓	—	—	—	—	3	—
Cd-113m	—	—	—	—	—	—	—	✓	—	2	—
Sn-121	—	—	—	—	—	—	—	—	✓	2	—
Sn-126	—	—	—	—	✓	✓	—	—	✓	7	—
Sb-125	—	—	✓	—	✓	✓	✓	✓	—	13	✓
I-129	—	—	✓	—	✓	✓	—	—	✓	11	✓
Cs-134	✓	✓	—	✓	✓	✓	✓	✓	—	24	✓
Cs-135	—	—	—	—	✓	✓	—	—	✓	7	—
Cs-137	✓	✓	—	✓	✓	✓	✓	✓	✓	26	✓
Ce-144	✓	✓	✓	—	✓	—	✓	✓	—	22	✓
Pm-147	—	✓	—	—	—	—	✓	✓	—	10	✓
Sm-151	—	—	—	—	—	—	—	—	✓	2	—
Eu-152	—	✓	—	—	✓	✓	✓	—	—	13	✓
Eu-154	—	—	—	—	✓	✓	✓	✓	—	9	—
Eu-155	—	—	—	—	—	—	✓	✓	—	4	—
Pb-210	—	—	—	—	✓	—	—	—	✓	5	✓
Ra-226	—	—	—	—	✓	—	—	—	✓	5	✓
Ra-228	—	—	—	—	✓	—	—	—	—	3	✓
Ac-227	—	—	—	—	✓	—	—	—	✓	5	✓

Table D-6 (continued)

Nuclide	Source (weighting factor)									Score	Include
	NUREG/ CR-0134	IAEA 1996	WINCO 1191	NUREG/ CR-0130	NUREG/ CR-3585	NUREG/ CR-4370	SAND 92 -0700	ORIGEN	SAND 91-2795		
	(5)	(6)	(4)	(4)	(3)	(2)	(2)	(2)	(2)		
Th-228	—	—	—	—	✓	—	—	—	—	3	✓
Th-229	—	—	—	—	✓	—	—	—	✓	5	✓
Th-230	—	—	—	—	✓	—	—	—	✓	5	✓
Th-232	—	—	—	—	✓	—	✓	—	—	5	✓
Pa-231	—	—	—	—	✓	—	—	—	✓	5	✓
U-232	—	—	—	—	✓	—	—	—	✓	5	—
U-233	—	—	—	—	✓	—	✓	—	✓	7	—
U-234	✓	✓	—	—	✓	✓	—	—	✓	18	✓
U-235	✓	✓	—	—	✓	✓	✓	—	✓	20	✓
U-236	—	—	—	—	✓	✓	✓	—	✓	9	—
U-238	✓	✓	—	—	✓	✓	✓	—	✓	20	✓
Np-237	—	✓	—	—	✓	✓	✓	✓	✓	17	✓
Pu-236	—	—	—	—	✓	✓	—	—	—	5	—
Pu-238	—	—	✓	—	✓	✓	✓	✓	✓	15	✓
Pu-239	✓	✓	✓	—	✓	✓	✓	✓	✓	26	✓
Pu-240	—	✓	✓	—	✓	✓	✓	✓	✓	21	✓
Pu-241	—	✓	—	—	✓	✓	✓	✓	✓	17	✓
Pu-242	—	—	—	—	✓	✓	✓	✓	✓	11	✓
Pu-244	—	—	—	—	✓	—	—	—	—	3	—
Am-241	✓	✓	—	—	✓	✓	✓	✓	✓	22	✓
Am-242	—	—	—	—	—	—	—	—	✓	2	—

Table D-6 (continued)

Nuclide	Source (weighting factor)									Score	Include
	NUREG/ CR-0134	IAEA 1996	WINCO 1191	NUREG/ CR-0130	NUREG/ CR-3585	NUREG/ CR-4370	SAND 92 -0700	ORIGEN	SAND 91-2795		
	(5)	(6)	(4)	(4)	(3)	(2)	(2)	(2)	(2)		
Am-242m	—	—	—	—	—	—	—	✓	—	2	—
Am-243	—	—	—	—	✓	✓	—	✓	✓	9	—
Cm-242	—	—	—	—	—	✓	—	—	—	2	—
Cm-243	—	—	—	—	✓	✓	—	✓	✓	9	—
Cm-244	—	✓	✓	—	✓	✓	✓	✓	✓	21	✓
Cm-245	—	—	—	—	—	—	—	✓	✓	4	—
Cm-246	—	—	—	—	—	—	—	—	✓	2	—
Cm-248	—	—	—	—	✓	—	—	—	—	3	—
Cf-252	—	—	—	—	✓	—	✓	—	—	5	—

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## **APPENDIX E**

### **DISTRIBUTION OF CONTAMINANTS DURING MELTING OF CARBON STEEL**

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## DISTRIBUTION OF CONTAMINANTS DURING MELTING OF CARBON STEEL

### E.1 INTRODUCTION

During the melting of potentially contaminated steel, the contaminants may be distributed among the metal product, the home scrap, the slag, the furnace lining, and the offgas collection system. In addition, some contaminants could pass through the furnace system and be vented to the atmosphere. In order to estimate the radiological impacts of recycling potentially contaminated scrap steel, it is essential to understand how the contaminants are distributed within the furnace system.

For example, a gaseous chemical element (e.g., radon) will be exhausted directly from the furnace system into the atmosphere while a relatively non-volatile element (e.g., manganese) can be distributed among all the other possible media. This distribution of potential contaminants is a complex process that can be influenced by numerous chemical and physical factors, including composition of the steel bath, chemistry of the slag, vapor pressure of the particular element of interest, solubility of the element in molten iron, density of the oxide(s), steel melting temperature, and melting practice (e.g., furnace type and size, melting time, method of carbon adjustment, and method of alloy additions).

This appendix discusses the distribution of various elements with particular reference to electric arc furnace (EAF) steelmaking. The next three sections consider the calculation of partition ratios for elements between metal and slag based on thermodynamic considerations<sup>1</sup>. Section E.5 presents laboratory and production measurements of the distribution of various elements among slag, metal, and the offgas collection system. Section E.6 proposes distributions for those elements where theoretical or practical information is lacking and Section E.7 provides recommendations for the assumed distribution of each element of interest.

### E.2 THERMODYNAMIC CALCULATION OF PARTITION RATIOS

Partitioning of a solute element between a melt and its slag under equilibrium conditions can be calculated from thermodynamic principles if appropriate data are available. Consider a divalent

---

<sup>1</sup> Reference to a given element does not necessarily imply that it is in the elemental form. For instance, a metallic element might be found in the elemental state in the melt while its oxide is found in the slag.

solute element M, such as cobalt, dissolved in molten iron, which reacts with FeO in the slag according to the following equation:



where  $\underline{M}$  is the symbol for solute dissolved in liquid iron.

Equation E-1 can be written as the difference between the following equations:



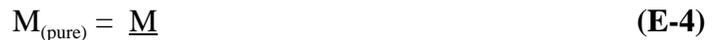
and



The Gibb's free energy for Equation E-1,  $\Delta F^\circ_1$  can be expressed as the difference in the free energies of Equations E-2 and E-3, viz.:

$$\Delta F^\circ_1 = \Delta F^\circ_2 - \Delta F^\circ_3$$

Thermodynamic data for Equation E-2 are normally tabulated assuming that the standard state for M is the pure liquid or solid, but it is often desirable to convert from the pure elemental standard state to a hypothetical standard state where M is in a dilute solution. In steelmaking, 1 wt% M in solution in iron is commonly used for this new standard state<sup>2</sup> as defined by the transformation:



The free energy change for M from the pure state to  $\underline{M}$  in the dilute state is (Darken and Gurry 1953):

$$\Delta F^\circ_4 = RT \ln \left( \frac{\gamma^\circ M_{\text{Fe}}}{100 M_{\text{M}}} \right)$$

---

<sup>2</sup> Concentrations are expressed here as wt% instead of mass % since wt% is commonly used in the steelmaking literature. The terms are synonymous.

- T = absolute temperature in kelvin (K)
- R = universal gas constant  
= 1.987 cal/mole·K
- $\gamma_M^\circ$  = Henry's Law activity<sup>3</sup> coefficient (based on atom fraction) of M at infinite dilution in iron
- $M_{Fe}$  = atomic weight of iron  
= 55.85
- $M_M$  = atomic weight of M

Equation E-2 can also be written as the difference of Equation E-5 (below) and Equation E-4.



Therefore,  $\Delta F_2^\circ = \Delta F_5^\circ - \Delta F_4^\circ$  and the Gibb's free energy change for Equation E-1 can be written as

$$\begin{aligned} \Delta F_1^\circ &= \Delta F_5^\circ - \Delta F_3^\circ - \Delta F_4^\circ \\ &= \Delta F_{f,MO}^\circ - \Delta F_{f,FeO}^\circ - RT \ln \left( \frac{\gamma^\circ M_{Fe}}{100 M_M} \right) \end{aligned} \quad (E-6)$$

where  $\Delta F_f^\circ$  is the free energy of formation of the particular oxide.

At equilibrium

$$\begin{aligned} \Delta F_1^\circ &= -RT \ln K_1 \\ &= -RT \ln \left( \frac{a_{Fe} a_{MO}}{a_{FeO} a_M} \right) \end{aligned} \quad (E-7)$$

where  $a$  is the activity of each species in Equation E-1 and  $K_1$  is the equilibrium constant. In the steel bath,  $a_{Fe}$  can be assumed to be 1, while  $a_{FeO} = \gamma_{FeO} N_{FeO}$ . To estimate  $N_{FeO}$  (the mole fraction of FeO in the slag), the nominal composition of the slag was assumed to be 50 wt% CaO, 30 wt% SiO<sub>2</sub>, and 20 wt% FeO. Thus,  $N_{FeO} = 0.167$ . Various investigators have described the activity of FeO in ternary mixtures of CaO, FeO, and SiO<sub>2</sub> (Philbrook and Bever 1951, Ansara

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<sup>3</sup> In Sections E.1, E.2, and E.3, activity refers to thermodynamic activity, not radioactivity.

and Mills 1984). For the slag composition assumed here, based on the ternary diagram by Ansara and Mills (1984), when  $N_{\text{FeO}}$  is 0.2,  $a_{\text{FeO}}$  is about 0.4 (i.e.,  $\gamma_{\text{FeO}}$  is about 2). Consequently,  $a_{\text{FeO}} = 0.333$ .

For the dilute standard state,  $a_{\text{M}}$  is equal to wt%  $\underline{\text{M}}$  and, for dilute solutions of MO in the slag, one can assume that  $a_{\text{MO}} = N_{\text{MO}}$ . It follows that

$$\frac{N_{\text{MO}}}{\text{wt}\% \underline{\text{M}}} = a_{\text{FeO}} \exp\left(\frac{-\Delta F_1^\circ}{RT}\right) \quad (\text{E-8})$$

where  $\frac{N_{\text{MO}}}{\text{wt}\% \underline{\text{M}}}$  is one form of the partition ratio for M between the melt and the slag.

For metal oxides other than those formed from divalent cations, the different stoichiometries must be accommodated in Equations E-6, E-7, and E-8.

Using values of  $\gamma^\circ$  for various solute elements in iron at 1,873 K tabulated by Sigworth and Elliott (1974)<sup>4</sup> and free energy of formation data for oxides tabulated by Glassner (1957), partition ratios between melt and slag were calculated for the present analysis and are presented in Table E-1. Values in the last column of Table E-1 will be described in Section E.3.

When the partition ratio is large, the solute element is strongly concentrated in the slag under equilibrium conditions. This is true for Al, Ce, Nb, Ti, U, and Zr, which all have partition ratios (as defined here) of 80,000 or greater. Similarly, when the partition ratio is small, the solute element is concentrated in the molten iron. Examples of this are Ag, Co, Cr, Cu, Ni, Pb, Sn, Mo, and W, which all have partition ratios of 0.008 or less. Mn, Si, and V, with partition ratios ranging from about 3 to 40, are expected to be more evenly distributed between melt and slag. Silver will not react with FeO in the slag, so on the basis of slag/metal equilibria, this element should remain in the melt. However, silver has a relatively high vapor pressure at steelmaking temperatures (i.e.,  $10^{-2}$  atm at 1,816 K), so some would tend to be removed at a rate dependent on the rate of transfer of silver vapor through the slag.

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<sup>4</sup> The value of  $\gamma^\circ$  for cerium is from Ansara and Mills 1984. A compendium of values for  $\gamma^\circ$  similar to that by Sigworth and Elliot 1974 has been prepared by the Japan Society for the Promotion of Science (1988). Some differences exist between values in Sigworth and Elliot 1974 and JSPS 1988, particularly for W, Co, Pb, and Ti. JSPS 1988 proposes a value of  $\gamma^\circ$  for  $\text{Ce}_{(l)}$  of 0.332. This difference in  $\gamma^\circ$  values does not affect the conclusions about cerium partitioning.

Table E-1. Partition Ratios at 1,873 K for Various Elements Dissolved in Iron and Slag

M	Oxide	$\gamma_M^\circ$	$\Delta F_{f,MO}^\circ$ (kcal/mole) <sup>a</sup>	Partition Ratio	
				( $N_{MO}/wt\%M$ )	(mass in slag/ mass in metal)
Ag <sub>(l)</sub>	Ag <sub>2</sub> O	200	+20.6	3.89e-04 <sup>b,c</sup>	
Al <sub>(l)</sub>	Al <sub>2</sub> O <sub>3</sub>	0.029 <sup>d</sup>	-257	1.32e+05 <sup>b</sup>	
Ca <sub>(g)</sub>	CaO	2240	-104	1.53e+09	1.1e+10
Ce <sub>(l)</sub>	CeO <sub>2</sub>	0.026	-176	4.33e+07	1.1e+09
Co <sub>(l)</sub>	CoO	1.07	-18.2	4.79e-05	5.0e-04
Cr <sub>(s)</sub>	Cr <sub>2</sub> O <sub>3</sub>	1.14	-80.0	1.21e-04 <sup>b</sup>	
Cu <sub>(l)</sub>	Cu <sub>2</sub> O	8.6	-11.0	1.99e-03 <sup>b</sup>	
Mn <sub>(l)</sub>	MnO	1.3 <sup>e</sup>	-58.0	2.74e+00	2.7e+01
Mo <sub>(s)</sub>	MoO <sub>3</sub>	1.86	-89.1	1.23e-05	2.1e-04
Nb <sub>(s)</sub>	Nb <sub>2</sub> O <sub>5</sub>	1.4	-275	8.12e+04 <sup>b</sup>	
Ni <sub>(l)</sub>	NiO	0.66	-19.0	3.72e-05	3.9e-04
Pb <sub>(l)</sub>	PbO	1400	-15.5	8.55e-03	3.2e-01
Si <sub>(l)</sub>	SiO <sub>2</sub>	0.0013	-129	3.76e+01	1.9e+02
Sn	SnO <sub>2</sub>	2.8	-47.6	6.07e-06	1.3e-04
Ti <sub>(s)</sub>	TiO <sub>2</sub>	0.038	-147	7.72e+04	6.6e+05
U <sub>(l)</sub>	UO <sub>2</sub>	0.027	-180	8.87e+07	3.8e+09
V <sub>(s)</sub>	V <sub>2</sub> O <sub>5</sub>	0.1	-206	7.68e+00 <sup>b</sup>	
W <sub>(s)</sub>	WO <sub>3</sub>	1.2	-96.2	2.77e-05	9.1e-04
Zr <sub>(s)</sub>	ZrO <sub>2</sub>	0.037	-178	1.59e+08	2.6e+09

<sup>a</sup>  $\Delta F_{f,FeO}^\circ = -34.0$  kcal/mole

<sup>b</sup>  $PR = N^{1/2}/wt\% M$

<sup>c</sup> Ag will not react with FeO, Ag<sub>2</sub>O unstable at 1,873K

<sup>d</sup> According to Ansara and Mills (1984),  $\gamma_{Al}^\circ = 0.005$

<sup>e</sup> According to Ansara and Mills (1984),  $\gamma_{Mn}^\circ = 1.48$

It is instructive to examine the impact of assuming a dilute solution in iron rather than the pure element as the standard state for the solute. For those elements that tend to partition strongly to the melt (Co, Cr, Cu, Mo, Ni, Sn, and W), change of standard state from the pure metal to the dilute solution increases partitioning to the melt by factors of about 10 to 300. Lead is an exception, presumably due to its strong deviation from ideal solution behavior. Similarly, use of a dilute solution as the standard state decreases partitioning to the slag for the strong oxide formers such as Al, Ce, Nb, Ti, U, and Zr by factors of about 100 to 16,000. The exception is

calcium with strong positive deviation from ideality. These observations emphasize the importance of using a dilute solution as the standard state when adequate data are available.

As noted previously, the calculations in Table E-1 assumed, for simplicity, that the activity of MO in the slag was equal to the mole fraction (i.e.,  $\gamma_{MO} = 1$ ). This may not be a good assumption. If, for example,  $\gamma_{MO} = 0.01$ ,  $N_{MO}$  would increase 100-fold. Work by Ostrovski (1994) on the partitioning of tungsten in steel melted in a 25-t EAF illustrates the impact of melting practice and slag chemistry on the activity of  $WO_3$  in the slag. When the steel was melted under strongly oxidizing conditions utilizing a 30-minute oxygen blow, the activity coefficient was found to be a function of the ratio %CaO:%SiO<sub>2</sub> in the slag and varied from about 10<sup>-2</sup> to about 10<sup>-4</sup> as the CaO:SiO<sub>2</sub> ratio increased from 1:1 to 4:1. Typical measured values of  $\log \frac{(\text{wt}\% \text{ W})}{[\text{wt}\% \text{ W}]}$  were between 1 and 2, where (% W) and [% W] are the tungsten contents of

the slag and the metal, respectively<sup>5</sup>. A good fit between experimental and calculated partition ratios was obtained using the following equations:

$$\log \gamma_{WO_3} = -2.076 - 0.592 \frac{(\%CaO)}{(\%SiO_2)}$$

and

$$\log \frac{(\%W)}{[\%W]} = \frac{3054}{T} - 4.56 - \log \gamma_{WO_3} + 3 \log a_{FeO} + \log \frac{M_w}{M_{WO_3}} + \log \left[ M_{WO_3} (n_{FeO} + n_{CaO} + n_{SiO_2} + n_{WO_3}) \right]$$

where  $n$  is the number of moles per 100 grams of the various slag components. With this melting practice, approximately 94% of the tungsten in the feed was transferred to the slag, 4% remained in the melt, and the balance was lost. This emphasizes that special melting practices can produce substantially different results from the predictions in Table E-1.

The thermodynamic treatment used to derive the partition ratios in Table E-1 assumes that the melt is a binary system of iron and solute M, while in practice the melt will actually be a multi-component solution. In recent years, a considerable amount of work has been done to develop, both theoretically and experimentally, a solution model which considers interactions between

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<sup>5</sup> The convention of using (x) and [y] to signify concentrations or components in the slag and the metal, respectively, is commonly used in the technical literature and will generally be used in this appendix.

solute elements (Engh 1992, Sigworth and Elliot 1974, Ansara and Mills 1984). The activity of element  $i$  in dilute solution can be expressed as:

$$a_i = f_i (\text{wt\% } i)$$

where  $f_i$  is the Henry's Law activity coefficient (for concentrations expressed in wt%). The first order interaction coefficients  $e_i^j$  are defined by the equation

$$\log f_i = \sum_{j=2}^k e_i^j (\% j)$$

(Higher order terms are possible but are not considered here.) Using, for illustrative purposes, a low alloy 4140 steel with the nominal composition 0.4% C, 0.04% S, 0.9% Cr, and 0.1% Co, and the interaction coefficients for cobalt with these elements in liquid iron from Engh 1992,  $f_{\text{Co}}$  was calculated to be 0.975. For this example, the impact of the binary interactions on cobalt activity in iron is quite small. Unfortunately, interaction coefficients for many of the elements of interest in the melting of potentially contaminated scrap metals are not available to refine the calculations summarized in Table E-1.

### E.3 CORRELATION WITH OTHER FORMS OF PARTITION RATIO

In the literature, the partition ratio (PR) may be expressed in a variety of ways. For example, in Chapter 9 of SCA 1995, partition ratios are expressed as "mass in slag/mass in steel." It is of interest to compare this formulation with the definition in column 5 of Table E-1 (i.e.,  $N_{\text{MO}}/\text{wt\% } \underline{M}$ ). The SCA 1995 PR may be expanded as:

$$\text{PR} = \frac{(\text{wt\% } \underline{M}) m_g}{[\text{wt\% } \underline{M}] m_s} \quad (\text{E-9})$$

$m_g$  = mass of slag

$m_s$  = mass of steel

and, if one assumes that the relevant reaction is that in Equation E-2, one can write:

$$\text{PR} = \frac{(\text{wt\% } \text{MO}) m_g M_{\underline{M}}}{[\text{wt\% } \underline{M}] m_s M_{\text{MO}}} \quad (\text{E-10})$$

where  $M_M$  and  $M_{MO}$  are the atomic weight of M and the molecular weight of MO, respectively.

Equation E-10 is based on the premise that the reaction involves a divalent solute metal. It is equally true for all oxides where the ratio of the anion to the cation is an integer. For simplicity, if one assumes that the slag consists of two oxide components MO and RO and that wt% MO is  $\ll$  wt% RO, then one can write that

$$N_{MO} = \frac{(\text{wt}\% \text{ MO})/M_{MO}}{100/M_{RO}} \quad (\text{E-11})$$

or that

$$(\text{wt}\% \text{ MO}) = \frac{100 N_{MO} M_{MO}}{M_{RO}} \quad (\text{E-12})$$

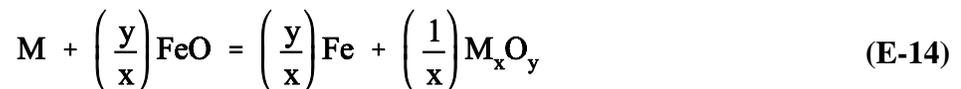
which can be substituted into Equation E-10 to give

$$PR = \frac{100 N_{MO} m_g M_M}{[\text{wt}\% \underline{M}] m_s M_{RO}} \quad (\text{E-13})$$

Equation E-13 relates the partition ratio as defined in SCA 1995 to that in Table E-1. Column 6 of Table E-1 converts the partition ratios in column 5 to the formulation in SCA 1995 (i.e., mass in slag/mass in metal), using the assumptions and simplifications described above, and further assuming that the ratio, mass of slag : mass of metal is 1:10 and RO is CaO. This conversion is only done for those oxides where the anion/cation ratio is an integer.

#### E.4 ESTIMATES OF THE PARTITIONING OF OTHER CONTAMINANTS

Values of the Henry's Law activity coefficient ( $\gamma_M^\circ$ ) are not available for many solute elements of interest in recycling potentially contaminated steel scrap. However, an indication of partitioning between the melt and the slag can be obtained by calculating the Gibb's free energy for the reaction



where M is the pure component rather than the solute dissolved in the melt and FeO and  $M_xO_y$  are slag components. Values of the standard free energy change for Equation E-14 are summarized in Table E-2 for all instances where the reaction occurs in the direction written.

Table E-2. Standard Free Energy of Reaction of Various Contaminants with FeO at 1,873 K

Element	Oxide	$\Delta F^\circ$ (kcal)	Comments
Ac <sub>(l)</sub>	Ac <sub>2</sub> O <sub>3</sub>	-120	Ac should partition to slag
Am <sub>(l)</sub>	Am <sub>2</sub> O <sub>3</sub>	-103	Am should partition to slag
Ba <sub>(l)</sub>	BaO	-57.1	Ba should partition to slag
Bi <sub>(g)</sub>	Bi <sub>2</sub> O <sub>3</sub>		Bi will not react with FeO, some may vaporize from melt
Cd <sub>(g)</sub>	CdO		CdO unstable at 1873 K, Cd should vaporize from the melt
Cs <sub>(l)</sub>	Cs <sub>2</sub> O		Cs <sub>2</sub> O unstable at 1873 K, Cs should vaporize from melt, some Cs may react with slag components
Ir <sub>(s)</sub>	IrO <sub>2</sub>		IrO <sub>2</sub> unstable above $\approx 1100$ K, Ir should remain in melt
K <sub>(g)</sub>	K <sub>2</sub> O		K <sub>2</sub> O less stable than FeO, other K compounds stable in slag
Na <sub>(g)</sub>	Na <sub>2</sub> O		Na <sub>2</sub> O less stable than FeO, other Na compounds stable in slag
Np <sub>(l)</sub>	NpO <sub>2</sub>	-100	Np should partition to slag
Pa <sub>(l)</sub>	PaO <sub>2</sub>	-94.7	Pa should partition to slag
Po <sub>(g)</sub>	PoO <sub>2</sub>		PoO <sub>2</sub> unstable above $\approx 1300$ K, Po assumed to vaporize from melt
Pu <sub>(l)</sub>	PuO <sub>3</sub>	-103	Pu should partition to slag <sup>a</sup>
Ra <sub>(g)</sub>	RaO	-47.7	Ra should partition to slag
Re <sub>(s)</sub>	ReO <sub>2</sub>		Re will not react with FeO, Re should remain in melt
Ru <sub>(s)</sub>	RuO <sub>4</sub>		RuO <sub>4</sub> unstable above $\approx 1700$ K, Ru should remain in melt
Sb <sub>(g)</sub>	Sb <sub>2</sub> O <sub>3</sub>		Sb will not react with FeO, some may vaporize from melt
Se <sub>(g)</sub>	SeO <sub>2</sub>		Se will not react with FeO, some may vaporize from melt
Sm <sub>(l)</sub>	Sm <sub>2</sub> O <sub>3</sub>	-102	Sm should partition to slag
Sr <sub>(g)</sub>	SrO	-58.6	Sr should partition to slag, but low boiling point could cause some vaporization
Tc <sub>(s)</sub>	TcO <sub>2</sub>		Tc will not react with FeO, should remain in melt
Th <sub>(s)</sub>	ThO <sub>2</sub>	-142	Th should partition to slag
Y <sub>(l)</sub>	Y <sub>2</sub> O <sub>3</sub>	-101	Y should partition to slag
Zn <sub>(g)</sub>	ZnO		Zn will not react with FeO, Zn should vaporize from melt

<sup>a</sup> The reaction between Pu and FeO to form PuO<sub>2</sub> is slightly more forward thermodynamically than the reaction to form Pu<sub>2</sub>O<sub>3</sub>.

Table E-2 shows that Ac, Am, Ba, Np, Pa, Pu, Ra, Sm, Sr, Th, and Y all will react with FeO to form their respective oxides as indicated by the calculated free energies. Thus, these elements should be preferentially distributed to the slag. By chemical analogy to similar species in Table E-1, one can estimate that the partition ratios ( $N_{MO}/wt\% M$ ) should be on the order of  $10^4$  or greater<sup>6</sup>. The solute elements Bi, Cd, Cs, Ir, K, Na, Re, Ru, Sb, Se, Tc, and Zn do not react with FeO either because the oxides are unstable or because Equation E-14 is thermodynamically unfavorable. Of these elements, Ir, Re, Ru, and Tc are expected to remain in the melt. As indicated in Table E-3, the solute elements Bi, Cd, Cs, Po, Sb, Se, and Zn have low boiling points and would be expected to vaporize from the melt to some degree at typical steelmaking temperatures of 1,823 K to 1,923 K. For example, cesium would tend to be removed at a rate dependent on the rate of transfer of vapor through the slag unless some stable compound such as  $Cs_2SiO_3$  forms in the slag. Should  $Cs_2O$  form during the melting process before a continuous slag had formed, it would be volatilized since the boiling point of the oxide is about 915 K. The boiling point of metallic cesium is in the same temperature range. Even though an element may have a low boiling point, it cannot be assumed, a priori, that the element will completely vaporize from the melt. Some may remain in the melt and some may be contained in the slag. For example, elements such as Ca, Mg, K, and Na are found as oxides and silicates in steel slags (Harvey 1990).

Pehlke (1973) has shown that, for a solute M dissolved in a solvent (liquid Fe), the following equation applies:

$$P_M(T) = P_M^\circ(T) \gamma_M(T) N_M \quad (E-15)$$

$P_M$  = vapor pressure of M over melt

$P_M^\circ$  = vapor pressure of pure M

$\gamma_M$  = activity coefficient of M in melt

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<sup>6</sup> The free energies in Table E-2 were recalculated assuming that  $\gamma^\circ$  in Equation E-6 was unity, and partition ratios were then calculated using Equation E-8. All partition ratios calculated in this manner for elements expected to partition to the slag were greater than  $10^4$  except Ba (6,300) and Ra (320). If all these calculated partition ratios were reduced by a factor of  $10^3$  to adjust for the fact that values of  $\gamma^\circ$  are expected to be less than unity, estimated partition ratios are greater than  $10^3$  for all slag formers except Ba (6.3), Ra (0.321), and Sr (15). These three elements are in Group II of the periodic table and have electronic structures and chemical properties similar to calcium. As discussed previously in Section E.2, calcium has a value of  $\gamma^\circ = 2,240$ . By analogy, one would expect that the partition ratios of Ba, Ra, and Sr would actually be higher than calculated with  $\gamma^\circ = 1$ . For example, if  $\gamma_{Ra}^\circ = 2,000$ , the partition ratio for radium, as defined by Equation E-8, would be  $6 \times 10^5$ .

$N_M$  = mole fraction of M in melt

Table E-3. Normal Boiling Point of Selected Potential Contaminants

Contaminant	Normal Boiling Point (K)
Bi	1900
Cd	1038
Cs	963
Pb	2010
Po <sub>2</sub>	1300
Ra	1410
S <sub>2</sub>	1890
Se <sub>2</sub>	1000
Sb <sub>2</sub>	1890
Zn	1180

Source: Darken and Gurry 1953

Thus, as the temperature of the melt increases, the quantity of the volatile element M in the melt decreases by an amount determined by the temperature dependency of  $P_M^\circ$ . Based on vapor pressure data for Pb, Sb, and Bi by Brandes and Brooks (1992) and Zn from Perrot et al. (1992), one can estimate that increasing the temperature of the iron bath from 1,873 K to 1,923 K will reduce the amount of Pb, Sb, and Bi by about 25% while that of Zn will be reduced by about 18% (assuming that  $\gamma_M$  is independent of temperature over the same range and  $P_M$  is constant). Actually,  $\gamma_M$  is an increasing function of temperature for antimony (Nassaralla and Turkdogan 1993) and a decreasing function for zinc (Perrot et al. 1992).

## E.5 OBSERVED PARTITIONING

This section discusses available experimental and production information on the distribution of possible contaminant elements among melt, slag, and the offgas collection system in steelmaking. Several of the key references are abstracted in Appendix E-1, which describes test conditions and relevant results from selected publications. Since many of the references cited in this section discuss the distribution of multiple elements in a single test, it would be cumbersome to repeat all the experimental details here for each element. Table E-4 summarizes the references by contaminant element. Substantial additional information on these and other references are presented by Worchester et al. (1993). Some additional perspective concerning the

concentrations of impurities and alloying elements can be obtained by examining the composition of a typical low carbon steel (i.e SAE 1020) as shown below:

- C ..... 0.18–0.23%
- Mn ..... 0.60–0.90%
- P ..... ≤ 0.04%
- S ..... ≤ 0.05%

Thus, the steel melting process must control carbon and manganese within specified ranges and insure that the maximum concentrations of sulfur and phosphorus are not exceeded. The furnace charge, the melting conditions, and the slagging practice must all be carefully managed to achieve the desired steel chemistry.

#### E.5.1 Americium

Based on the thermodynamic equilibria, americium would be expected to partition strongly to the slag. Gomer of British Steel reported that, when melting reactor heat exchanger tubing contaminated with Am-241 in a 5-t EAF, traces of Am-241 were found in the slag. No other Am-241 was detected (Pflugard et al. 1985). In laboratory steel melting experiments in a 5-kg furnace, the Am-241 distribution was 1% in the ingot, 110%<sup>7</sup> in the slag, and 0.05% in the aerosol offgas filter, resulting in a partition ratio between slag and metal of about 100 (Schuster and Haas 1990, Schuster et al. 1988). Americium is chemically similar to uranium which partitions strongly to the slag (Harvey 1990). On the basis of the available information, americium is expected to partition to the slag as predicted by the thermodynamic calculations. However, one caveat is offered by Harvey (1990). Since the density of the AmO<sub>2</sub> is high (11.68 g/cm<sup>3</sup>), transfer of americium to the slag may be retarded by gravity.

In small-scale laboratory experiments using mild steel (see Section E.5.20 for details), americium was observed to partition to the slag (Gerding et al. 1997). Ratios of the concentration of americium in slag to the concentration of americium in metal generally exceed 1000:1.

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<sup>7</sup> Because of differences in detection efficiencies, more radioactivity is sometimes detected in the products than was measured in the furnace charge.

Table E-4

## Selected References on the Distribution of Potential Contaminants During Steelmaking

Element	References
Ag	Sappok et al. 1990, Harvey 1990, Menon et al. 1990
Am	Pflugard et al. 1985, Schuster and Haas 1990, Schuster et al. 1988
C	Schuster and Haas 1990, Stubbles 1984b
Ce	Sappok et al. 1990, Harvey 1990
Co	Nakamura and Fujiki 1993, Pflugard et al. 1985, Sappok et al. 1990, Larsen et al. 1985a, Schuster and Haas 1990, Harvey 1990, Schuster et al. 1988, Menon et al. 1990
Cr	Stubbles 1984a
Cs	Nakamura and Fujiki 1993, Larsen et al. 1985a, Larsen et al. 1985b, Pflugard et al. 1985, Sappok et al. 1990, Harvey 1990, Menon et al. 1990
Eu	Sappok et al. 1990, Larsen et al. 1985a, Harvey 1990
Fe	Schuster and Haas 1990, Schuster et al. 1988
H	Stubbles 1984b
Ir	Larsen et al. 1985b
Mn	Nakamura and Fujiki 1993, Sappok et al. 1990, Stubbles 1984a, Meraikib 1993, Harvey 1990, Menon et al. 1990
Mo	Stubbles 1984a, Chen et al. 1993
Nb	Stubbles 1984a, Harvey 1990
Ni	Harvey 1990, Stubbles 1984a, Schuster and Haas 1990
P	Stubbles 1984b
Pb	Stubbles 1984a
Pu	Gerding et al. 1997, Harvey 1990
Ra	Starkey et al. 1961
S	Stubbles 1984b
Sb	Harvey 1990, Menon et al. 1990, Stubbles 1984a, Kalcioglu and Lynch 1991, Nassaralla and Turkdogan 1993
Sr	Nakamura and Fujiki 1993, Larsen et al. 1985b, Schuster and Haas 1990
Th	Harvey 1990
U	Harvey 1990, Larsen et al. 1985a, Schuster and Haas 1990, Heshmatpour and Copeland 1981, Abe et al. 1985
Zn	Harvey 1990, Nakamura and Fujiki 1993, Sappok et al. 1990, Stubbles 1984a, Menon et al. 1990
Zr	Stubbles 1984a

### E.5.2 Antimony

As described previously, antimony will not react with FeO in the slag and therefore is expected to remain in the melt. However, as noted in Table E-3, the normal boiling point of antimony (1890 K) is at steelmaking temperatures and at least some vaporization would be expected. Contrary to this prediction, Harvey (1990) reports "...that when antimony is added to steel it is recovered with high yield.". This view is supported by Philbrook and Bever (1951), who observed that antimony is probably almost completely in solution in steel. On the other hand, Stubbles (1984a) indicates that antimony is volatilized from scrap during EAF melting. In no case is adequate background information provided to support the statements<sup>8</sup>.

Kalcioglu and Lynch (1991) found that antimony could be removed from carbon-saturated iron (typical of blast furnace operations) if temperatures exceeded 1,823 K and the slag basicity,

$$B = \frac{(\text{CaO}) + (\text{MgO})}{(\text{SiO}_2) + (\text{Al}_2\text{O}_3)}$$

was greater than 1. Using very small samples consisting of 2 g of slag and 3 g of steel, about 45% to 51% of the antimony was vaporized at 1,823 K when the slag basicity was unity. The distribution of antimony between slag and metal is presented in Table E-5.

Table E-5. Distribution of Antimony Between Slag and Metal

[wt%Sb] <sup>a</sup>	L <sub>Sb</sub> <sup>b</sup>
0.40	0.55
0.46	0.59
0.51	0.67

<sup>a</sup> [wt%Sb] = concentration in metal

<sup>b</sup> L<sub>Sb</sub> = (wt%Sb)<sub>metal</sub> / (wt%Sb)<sub>slag</sub>  
(wt%Sb) = concentration in slag

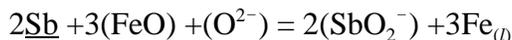
When the slag basicity was 0.818, values of L<sub>Sb</sub> ranged from 0.09 to 0.13, and when the basicity was 0.666, L<sub>Sb</sub> ranged from 0.05 to 0.08 at 1,823 K. The reaction which caused the marked

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<sup>8</sup> In a recent telephone conversation, Dr. J. R. Stubble, currently Manager of Technology at Charter Steel Company, advised that his conclusions in Stubbles 1984a were based on the high vapor pressure of antimony rather than experimental steel melting evidence. He would not argue against Harvey's conclusions (Stubbles 1996).

increase in antimony partitioning to the slag when the basicity was increased to 1 was not identified.

In a proposed follow-on study to the work of Kalcioglu and Lynch, Zhong (1994) suggested that the reaction



has an estimated value for  $\Delta F^\circ$  of -4 kcal. While not strongly favoring partition to the slag, the reaction can proceed as written particularly since  $a_{\text{FeO}}$  and  $a_{\text{O}^{2-}}$  tend to be high in basic slags.

Using data presented by Zhong, the partition ratio for the above reaction can be roughly estimated to be 0.006—a value similar to those for copper and lead in Table E-1<sup>9</sup>. The calculation supports the conclusion that antimony will not partition to the slag to a significant degree.

This conclusion is reinforced by the work of Nassaralla and Turkdogan (1993) who stated that "...most of the antimony will remain in the metal phase. However, it should be possible to remove some antimony from the hot metal by intermixing it with lime-rich flux under highly reducing conditions." Using values of  $\gamma_{\text{Sb}}^\circ$  developed by these investigators, one can calculate a partition ratio for antimony of  $8 \times 10^{-6}$  at 1,873 K.

Based on calculated partition ratios (above and in Table E-1), vapor pressures of the pure metals (Table E-3), and vapor pressures of the metal oxides<sup>10</sup>, one would expect that antimony and lead would behave similarly. It is therefore unclear why antimony tends to remain in the melt and lead is primarily collected in the bag house. This may be a manifestation of significantly higher activity of lead as compared to antimony in molten iron.

Menon et al. (1990) measured the distribution of Sb-125 from two heats of stainless steel. Activities of  $4.3 \times 10^5$  Bq were detected in the melt and  $1.7 \times 10^3$  Bq in the baghouse dust. No activity was reported in the slag.

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<sup>9</sup> This calculation uses a value for  $\gamma_{\text{Sb}}^\circ$  measured in carbon-saturated iron.

<sup>10</sup> According to Perry and Green (1984), the vapor pressures of PbO and Sb<sub>4</sub>O<sub>6</sub> are one atmosphere at 1,745 K and 1,698 K, respectively.

### E.5.3 Carbon

Carbon is a carefully controlled element in steelmaking. Excess carbon is often added to the melt and then reduced to its final level by oxygen decarburization. This process promotes slag/metal reactions and assists in removing hydrogen from the melt (Stubbles 1984b). CO produced by the decarburization reaction combines with atmospheric oxygen in the offgas to form CO<sub>2</sub>, which is exhausted from the system (Philbrook and Bever 1951). If, for example, 5 kg/t of charge carbon are added to a melt that nominally contains 2.5 kg of carbon per tonne of scrap and the objective is to produce steel with a final carbon content of 0.2% (i.e., an SAE 1020 steel), 0.55 wt% C must be removed. Thus, about 73% of the carbon would be exhausted from the system and the balance would remain in the melt. The distribution of carbon between the melt and the offgas is dependent upon the carbon content of the scrap charge, the melting practice (i.e., use of charge carbon), and the desired carbon content of the finished steel.

### E.5.4 Cerium

Based on thermodynamic calculations, cerium should strongly partition to the slag as CeO<sub>2</sub> or Ce<sub>2</sub>O<sub>3</sub>. Sappok et al. (1990) have described experience in induction melting of contaminated steel from nuclear installations. All Ce-144 contamination was found in the slag, although details of the melting and slagging practice were not discussed. Cerium is sometimes added to steel to react with oxygen and sulfur. Since CeO<sub>2</sub> has a density of 6.9 g/cm<sup>3</sup>, which is similar to that of molten steel, Harvey (1990) suggests that the density of the oxide retards transfer to the slag and, consequently, some CeO<sub>2</sub> may remain as non-metallic inclusions in the steel.

According to JSPS (1988), Ce<sub>2</sub>O<sub>3</sub> rather than CeO<sub>2</sub> is the stable oxide during steelmaking. In addition, JSPS recommends a value of 0.322 for  $\gamma^\circ$  in dilute iron solutions. These differing assumptions do not alter the conclusion—developed from the calculations in Section E.2—that cerium strongly partitions to the slag. Using the data recommended by JSPS, the partition ratio

for cerium,  $\frac{N_{MO}^{1/2}}{\text{wt}\% \underline{M}}$ , is  $1.15 \times 10^8$ .

### E.5.5 Cesium

Based on free energy and vapor pressure considerations, cesium would be expected to volatilize from the melt. Furthermore, cesium has no solubility in liquid iron. According to ASM 1993:

From the scant data reported here and by analogy with other iron-alkali metal binary phase diagrams, it is evident that Cs-Fe is virtually completely immiscible in the solid and liquid phases.

A number of investigators have reported measurements on the experimental distribution of cesium during steel melting. Sappok et al. (1990) observed that during air induction melting of about 2,000 tons of steel, no Cs-134/137 remained in the melt. Cesium was found both in the slag and in the dust collection system but the distribution was not quantified.

At the Japanese Atomic Energy Research Institute (JAERI), Nakamura and Fujiki (1993) obtained similar results from air induction melting of both ASTM-A335<sup>11</sup> and SUS 304 steels. The Cs-137 was about equally distributed between the slag and the dust collection system, but only about 77% of the amount charged was recovered.

At the Idaho National Engineering Laboratory (INEL), Larsen et al. (1985a) found cesium both in the slag and in the baghouse dust when melting contaminated scrap from the Special Power Excursion Reactor Test (SPERT) III. In tracer tests, Larsen et al. (1985b) found that 5% to 10% of the cesium remained in Type 304L stainless steel ingots.

Gomer described results of three 5-t EAF and one 500-kg induction furnace melts in which the chemical form of cesium addition and the slag chemistry were varied (Gomer and Lambley 1985, Pflugard et al. 1985). The distribution of this nuclide, based on the fraction of Cs-134 recovered, is summarized in Table E-6.

Table E-6. Distribution of Cs-134 Following Steel Melting

Furnace Type	Cs Addition	Cs Distribution (%)			Cs Recovery (%)
		Steel	Slag	Off Gas	
EAF	CsCl	0	0	100	100
Induction	CsOH	0	100	0	91
EAF	CsOH	0	7	93	50
EAF	Cs <sub>2</sub> SO <sub>4</sub>	0	66	34	64

<sup>11</sup> This ASTM specification covers various seamless ferritic alloy steel pipes for high temperature service.

In the melt where the cesium was added as CsCl, the chloride, which is volatile below the steel melting temperature, was not collected in the slag because the slag had not formed before the CsCl had completely evaporated. In the induction furnace test, CsOH was added to the liquid steel under a quiescent acid slag. In the related arc furnace test with CsOH, the slag was not sufficiently acid to promote extensive formation of cesium silicate, which would be retained in the slag. In the arc furnace melt with the Cs<sub>2</sub>SO<sub>4</sub> addition, this compound was apparently incorporated into the slag to a significant extent.

Harvey (1990) concluded that the hot, basic slags typical of EAF melting were not conducive to cesium retention in the slag. A comparison of three arc furnace melts with varying slag compositions showed the following amounts of cesium retention in the slag 16 minutes after cesium was added to the melt:

- SiO<sub>2</sub>:CaO = 3.1:1 ..... 50% recovery
- SiO<sub>2</sub>:CaO = 1.3:1 ..... < 4% recovery
- SiO<sub>2</sub>:CaO = 0.41:1 ..... 0 recovery

In these tests, no cesium remained in the melt.

Menon et al. (1990) recounted that no cesium was found in the ingots or the slag after melting 332 metric tons (t) of carbon steel in an induction furnace, but that substantial Cs-137 (21,000 Bq/kg) was collected in the ventilation filters. During production of two heats of stainless steel, no cesium was found in the ingots; 32% was in the slag; and 68% in the baghouse dust (Menon et al. 1990).

#### E.5.6 Chlorine

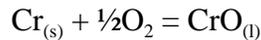
The disposition of chlorine depends on its form at the time of introduction into the EAF furnace. Any chlorine gas would be desorbed from the scrap metal surface and vented to the atmosphere. If the contaminant exists as a metal chloride, it is likely to be distributed between the slag and the baghouse dust. Cl<sup>-</sup> has been reported in baghouse dust (McKenzie-Carter et al. 1985).

#### E.5.7 Chromium

From a theoretical viewpoint, chromium would be expected to remain primarily in the melt. However, Stubbles (1984a) suggests that chromium recovery in the melt during EAF steelmaking

is only 30% to 50%. Stubbles' observation is not consistent with the calculations in Table E-1, which show chromium remaining primarily in the melt.

Xiao and Holappa (1993) have studied the behavior of chromium oxides in various slags at temperatures between 1,773 K and 1,873 K. They reported that chromium in the slag was mainly (i.e., 88% to 100%)  $\text{Cr}^{2+}$  when the mol%  $\text{CrO}_x$  in the slag was 10% or less and the  $N_{\text{CaO}}:N_{\text{SiO}_2}$  ratio was unity. The calculations in Table E-1 assumed  $\text{Cr}^{+3}$  to be the predominant species. Using free energy data presented by these authors for the reaction



( $\Delta F^\circ = -79,880 + 15.25 T \text{ cal}$ ) and other relevant data from Table E-1, the partition ratio involving CrO rather than  $\text{Cr}_2\text{O}_3$  is calculated to be 0.42. This suggests that a significant portion of the chromium will partition to the slag if  $\text{Cr}^{+2}$  is the principal cation in the slag.

#### E.5.8 Cobalt

Free energy calculations indicate that cobalt should remain primarily in the melt. Nakamura and Fujiki (1993) found this to be the case in 500-kg air induction melts of carbon steel and stainless steel where Co-60 was detected only in the ingots. During the melting of six heats of contaminated carbon steel scrap at INEL, some (unquantifiable) Co-60 activity was detected in the dust collection system and some in the slag (Larsen et al. 1985a). In subsequent tracer tests with three heats of Type 304L stainless steel, between 96% and 97% of the Co-60 was recovered in the ingots (Larsen et al. 1985b). Sappok et al. (1990) noted that, during the induction melting of steel, Co-60 was mostly found in the melt although unquantifiable amounts were detected in the slag and in the dust collection system. In an earlier paper, Sappok cited the Co-60 distribution from nine melts totaling 24 t as 97% in the steel, 1.5% in the slag, and 1.5% in the cyclone and baghouse (Pflugard et al. 1985). Schuster and Haas (1990) measured the Co-60 distribution in laboratory melts of St37-2 steel and reported 108% in the ingot, 0.2% in the slag, and 0.2% in the aerosol filter.

According to Harvey (1990), "...cobalt-60 will almost certainly be retained entirely in the steel in uniform dilution in both electric arc and induction furnaces." In support of this conclusion, Harvey described two steel melts in a 5-t EAF. In one test, highly reducing conditions were employed (high carbon and ferrosilicon) while, in the other, the conditions were oxidizing

(oxygen blow). In neither case was any measurable cobalt activity found in the slag. The amount of Co-60 found in the melt was in good agreement with the amount predicted from the furnace charge. No Co-60 was found in the furnace dust although some was expected based on transfer of slag and oxidized steel particles to the gas cleaning system. Harvey concluded that the low level of radioactivity in the furnace charge (ca. 0.23 Bq/g) coupled with dilution from dust already trapped in the filters resulted in quantities of Co-60 in the offgas below the limits of detection.

Menon et al. (1990) commented on the air induction melting of 33.6 t of carbon steel. No Co-60 was detected in the slag, but a small quantity (1,300 Bq/kg) was detected in the baghouse dust. The amount remaining in the ingots was not quoted. In two heats of stainless steel weighing a total of 5 t, 26 MBq of Co-58/Co-60 were measured in the ingots, 40 kBq in the slag, and 78 kBq in the baghouse dust.

#### E.5.9 Europium

Based on its chemical similarity to other rare-earth elements such as samarium, cerium, and lanthanum, europium is expected to partition to the slag. During induction melting of steel scrap from nuclear installations, Sappok et al. (1990) reported that all the Eu-154 was in the slag. Larsen found some europium in the slag and some in the baghouse dust during induction melting of scrap from the SPERT III reactor. The europium content was below the limits of detection in the feed material, so presumably some unquantified concentrating effects occurred in the slag and the offgas dust (Larsen et al. 1985a). Eu-152 concentrations in the baghouse dust were very low—on the order of 0.8 pCi/g. Harvey (1990) described production of an experimental 3.5-t melt of steel in an arc furnace to study europium partitioning. During the melting operation, oxygen was blown into the melt to remove 0.2% C (typical of normal steelmaking practice). The radioactivity of the metal was too low to be measured and no europium was found in the dust from the fume extraction system. Europium activity was detected only in the slag. Even though there was some concern expressed that, because of the similar densities of steel and  $\text{Eu}_2\text{O}_3$  (7.9 g/cm<sup>3</sup> and 7.4 g/cm<sup>3</sup>, respectively), the  $\text{Eu}_2\text{O}_3$  would not readily float to the metal/slag interface, the experimental results suggest this was not an issue. With regard to the fact that no europium was found in the fume collection system, Harvey (1990) observed:

It is inevitable, however, because of the nature of the process, that some slag is ejected into the atmosphere of the arc furnace and is then entrained in the offgas and is collected in the gas cleaning filters. Hence any radioactive component present in the slag will be present to

some extent in the offgas. The fact that it is not detected on this occasion reflects the small amount of radioactivity used, and the mixing and dilution of dust which occurs in the gas cleaning plant.

#### E.5.10 Hydrogen

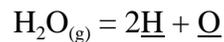
Hydrogen is an undesirable impurity in steel, causing embrittlement. Thus steelmaking practice seeks to keep the contaminant at very low levels. As noted in Section E.5.3, removal of charge carbon by blowing oxygen through the melt reduces the hydrogen as well. Stubbles (1984b) described tests on the rate of hydrogen removal as a function of time and carbon reduction rate. For steel with an initial hydrogen content of 9 ppm, the hydrogen level was reduced to 1 ppm after 15 minutes when the rate of carbon removal was 1% per hour and to 5 ppm over the same interval when the carbon removal rate was 0.1% per hour.

Stubbles' work is consistent with results reported by Deo and Boom (1993) who showed that the rate of hydrogen removal was directly related to the rate of carbon removal. They also described the work of Kreutzner (1972) who investigated the solubility of hydrogen in steel at 1,873 K and 1,973 K. From a graphical presentation of Kreutzner's work, one can estimate that the solubility of hydrogen in steel at 1,873 K can be expressed as

$$[\text{H}] = 27 P_{\text{H}_2}^{1/2}$$

where [H] is the hydrogen solubility in ppm and  $P_{\text{H}_2}$  is the hydrogen partial pressure in atmospheres. Thus, when  $P_{\text{H}_2}$  is 0.01 atm, the equilibrium hydrogen concentration is 2.7 ppm.

Since the most likely source of hydrogen is from water in the charge components or the furnace atmosphere, the following reaction should also be considered (Philbrook and Bever 1951):



At 1,873 K, the equilibrium hydrogen concentration is

$$\% \text{H} = 1.35 \cdot 10^{-3} \left( \frac{P_{\text{H}_2\text{O}}}{a_{\text{O}}} \right)^{1/2}$$

where  $a_{\text{O}}$  is the activity of oxygen in the melt. One can see from this equation that the % $\underline{\text{H}}$  increases as  $a_{\text{O}}$  decreases. Table E-7 lists the concentrations of  $\underline{\text{H}}$  for various assumed dissolved oxygen concentrations when  $P_{\text{H}_2\text{O}}$  is 0.003 atm.

Table E-7. Hydrogen and Oxygen Concentrations in Liquid Iron ( $P_{\text{H}_2\text{O}} = 0.003$  atm)

Concentration (%)	
$\underline{\text{O}}$	$\underline{\text{H}}$
0.1	2.5e-04
0.01	8e-04
0.001	2.5e-03

If the oxygen content of the bath is low, the steel can absorb more hydrogen from water vapor than from pure hydrogen at 1 atm. Hydrogen or water vapor in materials added to the bath after carbon removal or to the furnace ladle will tend to be retained in the product steel (Philbrook and Bever 1951).

#### E.5.11 Iridium

Iridium would be expected to remain in the melt during steelmaking. Iridium and iron are completely miscible in the liquid phase (ASM 1993). INEL conducted one induction melting test at the Waste Experimental Reduction Facility (WERF) where Ir-192 was added to Type 304L stainless steel to produce about 500 lb of product. About 60% of the charged iridium was recovered in the ingot but only small quantities were detected in the slag. Although the material balance was poor, there is no basis to conclude that iridium does not primarily remain in the melt (Larsen et al. 1985b).

#### E.5.12 Iron

Iron oxide is a major slag component. According to a 1991 survey by the National Slag Association, the average FeO content of steel slags is 25% (NSA 1994). If one assumes that the ratio of slag mass to steel mass is 0.1, then about 2% of the iron in the charge would be distributed to the slag. Schuster et al. reported some laboratory tests where Fe-55 was added to small melts of steel conducted under an Ar + 10% H<sub>2</sub> atmosphere and reducing conditions (Schuster and Haas 1990, Schuster et al. 1988). No Fe-55 was found in the slag or the aerosol

filter. However, these results have little relevance to expected partitioning under actual steelmaking conditions.

#### E.5.13 Lead

As shown in Table E-1, lead should remain with the melt rather than with the slag. At 1,873 K, lead has limited solubility in molten iron—about 0.064 to 0.084 wt% (ASM 1993). Although the boiling point of lead (2,010 K) is above normal steelmaking temperatures, lead has a significant vapor pressure (ca. 0.4 atm) at 1,873 K. In addition, any PbO which forms during initial heating of the furnace charge could volatilize before the steel begins to melt since PbO is a stable gas at steelmaking temperatures (Glassner 1957, Kellog 1966). Consequently, much of the lead should be transferred from the melt either as lead vapor or as gaseous PbO and be collected in the offgas system. Stubbles (1984a) reports that, when leaded scrap is added to liquid steel, the lead boils off like zinc and is collected with the fume. If lead in the form of batteries or babbitts is added to the furnace charge, the lead will quickly melt and sink to the bottom of the furnace where it may penetrate the refractory lining.

#### E.5.14 Manganese

Manganese is a common element in steelmaking. As discussed above, a typical carbon steel contains 0.6 to 0.9% Mn. Calculations in Section E.2 show that manganese should be more concentrated in the slag than in the metal. For EAF melting, Stubbles states that about 25% of the manganese is recovered in the steel. This establishes the partition ratio based on the mass of manganese in slag to the mass of manganese in steel at 3:1.

Meraikib (1993) compiled information on manganese distribution between slag and molten iron based on a large number of heats in a 70-ton EAF. He showed that the ratio of the concentration of manganese in the slag to manganese in the metal,  $\eta_{Mn}$ , is given by the following equation:

$$\eta_{Mn} = \frac{(Mn)}{[Mn]}$$

$$= a_{[O]} f_{[Mn]} \exp \left( \frac{27530}{T} - 0.0629 B - 7.3952 \right)$$

(Mn) = concentration of Mn in slag (wt%)

[Mn] = concentration of Mn in melt (wt%)

$a_{[O]}$  = activity of oxygen in melt

$f_{[Mn]}$  = activity coefficient for [Mn]

All other terms have been defined previously.

For the range of manganese concentrations (0.06 to 1.0 wt%) and the range of temperatures (1,823 K to 1,943 K) studied,  $f_{[Mn]}$  is essentially unity (i.e., 0.9503). If one assumes that  $B = 2$  and  $a_{[O]} = 0.004$ , then the variation of  $\eta_{Mn}$  with temperature can be calculated as follows:

1,843 K .....  $\eta_{Mn} = 6.3$

1,943 K .....  $\eta_{Mn} = 2.9$

indicating that the ratio of the concentrations manganese in slag and in metal can vary by a more than factor of two for a 100 K change in melt temperature. Based on the work of Meraikib, the partitioning of manganese between slag and metal (assuming a slag:metal ratio of 1:10) is an order of magnitude lower than observed by Stubbles and about two orders of magnitude lower than estimated from thermodynamic principles in Section E.2. This suggests that the oxygen activity in the steel in equilibrium with the slags used in Meraikib's work is lower than implied in the free energy calculations in Section E.2

Nakamura and Fujiki (1993) conducted four 500-kg air induction melting tests (two with ASTM-A335 steel and two with SUS 304 stainless steel) to which 24 MBq of Mn-54 were added. In two tests with SUS 304 and one test with ASTM-A335, about 90% of the activity was contained in the ingot, while in the other ASTM-A335 ingot only 50% of the Mn-54 was recovered. For the one ASTM-A335 ingot where the slag concentration was also reported, the distribution based on input radioactivity was:

- ingot ..... 91%
- slag ..... 8%
- unaccounted ..... 2%

Sappok et al. (1990) described experience in melting about 2,000 t of contaminated steel in a 20-ton induction furnace. The melting process generated only a small amount of slag (i.e., about 1.2%). During a 200-t melting campaign, no Mn-54 was found in the melt. Up to 21.9% of the

total slag activity was attributed to Mn-54 and up to 2.1% of the total activity in the dust collection system was from this nuclide.

Harvey (1990) notes that manganese tends to be more concentrated in the slag when melting under oxidizing conditions although the reverse result can be obtained when the furnace conditions are reducing. Manganese is relatively volatile having a vapor pressure of 0.08 atm at 1,900 K.

In two stainless steel heats melted at Studsvik, the combined manganese distribution was (Menon et al. 1990):

- ingot ..... 44 kBq
- slag ..... 3.6 kBq
- baghouse dust ..... 0.36 kBq

#### E.5.15 Molybdenum

As described previously in Section E.2, molybdenum should remain primarily in the melt. Stubbles (1984a) supports this view, indicating that 100% of molybdenum is recovered in the steel during EAF melting. Studies by Chen et al. (1993) on the reduction kinetics of MoO<sub>3</sub> in slag also buttress this conclusion. In 1-kg-scale laboratory tests, Chen found that the reduction of MoO<sub>3</sub> in slag over an iron-carbon melt was completed in about five minutes.

#### E.5.16 Nickel

Nickel is chemically similar to cobalt and should remain in the melt during steelmaking. Stubbles states that nickel recovery during arc melting is 100% (Stubbles 1984a). According to Harvey, it is common practice to add NiO to a steel melt and quantitatively recover the nickel. He further notes: "Nickel cannot be volatilized from molten steel, and there do not appear to be any slags which will absorb nickel selectively." (Harvey 1990). Schuster described the distribution of Ni-63 in laboratory melts of 3 to 5 kg under inert gas (Schuster and Haas 1990). About 82% of the nickel was recovered in the ingot, 0.04% in the slag and 0.06% in the aerosol filter, with the remainder unaccounted for.

### E.5.17 Niobium

On the basis of the thermodynamic calculations in Section E.2, niobium should partition primarily to the slag. According to Stubbles (1984a), the recovery of niobium from scrap in the ingot is zero during EAF melting, which is consistent with the theoretical calculations. Harvey (1990) notes that niobium can be retained in the steel under reducing conditions, but under oxidizing conditions will clearly be transferred to the slag according to the reaction:

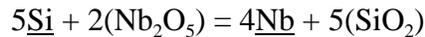


The equilibrium constant for this reaction is :

$$K_1 = \frac{a_{\text{FeO} \cdot \text{Nb}_2\text{O}_5}}{a_{\text{Fe}} a_{\text{Nb}}^2 a_{\text{O}}^6}$$

indicating that the equilibrium is very sensitive to the activity of the oxygen in the steel. At 1,873 K,  $K_1 = 2.4 \times 10^{10}$ .

Wenhua et al. (1990) studied the kinetics of  $\text{Nb}_2\text{O}_5$  reduction in slag by silicon dissolved in iron according to the reaction:



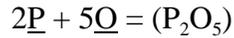
The reaction was assumed to be divided into five steps:

1.  $\text{Nb}_2\text{O}_5$  diffuses through slag towards reaction interface
2. Si diffuses through molten iron towards reaction interface
3. Reaction occurs at interface
4. Reaction product niobium diffuses from interface into molten iron
5. Reaction product  $\text{SiO}_2$  diffuses from interface into slag

Using a slag with a  $\text{CaO}:\text{SiO}_2$  (basicity) ratio of about 2:1 and a ferrosilicon reductant (ca 0.42% Si), niobium was rapidly transferred from the slag to the melt, reaching a value of 1.5% after 10 minutes. Wenhua found that the rate controlling step was the diffusion of niobium in liquid iron.

### E.5.18 Phosphorus

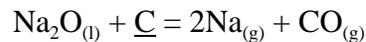
Phosphorus is an undesirable impurity in steel which is typically removed by oxidation. The transfer of phosphorus from the metal to the slag can be represented by the following simplified reaction (Stubbles 1984b):



The amount removed from the melt will depend on the phosphorus content of the scrap charge and the desired phosphorus content of the melt. Phosphorus removal is facilitated during EAF melting by increasing the basicity and oxidation level of the slag. By injecting 35 kg of powered lime per tonne into the melt together with oxygen, the phosphorus content can be reduced to about 10% of its initial value.

### E.5.19 Potassium and Sodium

Since  $\text{K}_2\text{O}$  is less stable than  $\text{FeO}$ , potassium should be removed from the melt because of its low boiling point. However, various potassium compounds such as silicates and phosphates are present in slags (Harvey 1990). The same considerations apply to sodium.  $\text{Na}_2\text{O}$  has also been collected in EAF baghouse dust (Brough and Carter 1972). Given the fact that  $\text{Na}_2\text{O}$  in the slag can be reduced by carbon in the melt (Murayama and Wada 1984), that observation is not surprising. The appropriate chemical equation is:



$\Delta F^\circ$  for this reaction at 1,873 K is -48 kcal/mole. Removal of  $\text{Na}_2\text{O}$  from the slag would be enhanced by higher carbon levels in the melt. Presumably, any sodium from this reaction would be vaporized and subsequently condensed in the baghouse as  $\text{Na}_2\text{O}$ .

### E.5.20 Plutonium

Thermodynamic predictions suggest that plutonium will partition strongly to the slag. Harvey assumed, based on the chemical similarity of plutonium with thorium and uranium, that the plutonium will form a stable oxide and be absorbed in the slag (Harvey 1990). However, he notes that because of its high specific gravity (11.5), transfer of  $\text{PuO}_2$  to the slag could be slow and some could possibly fall to the base of the furnace and not reach the slag.

Gerding et al. (1997) conducted small-scale (i.e., 10 g and 200 g) tests with plutonium oxide and mild steel in an electric resistance furnace. The melts were held in contact with various slags for one to two hours at 1,773 K under helium at about 0.5 atm. Slag:steel weight ratios ranged from 0.05 to 0.20. The studies showed that the plutonium partitioned to the slag and the partition coefficients (concentration in slag ÷ concentration in metal) were  $2 \times 10^6$  to  $8 \times 10^6$ . Decontamination efficiency was about the same at 400 and 14,000 ppm Pu, and differences in composition among the various silicate slags were not significant to the partitioning.

#### E.5.21 Radium

Radium forms a stable oxide in the presence of FeO and thus would be expected to be found mainly in the slag. Starkey et al. (1961) described results from the arc furnace melting of eight heats of steel contaminated with radium. The average concentration of the radium in the steel was  $<9 \times 10^{-13}$  g Ra/g steel and in the slag was  $1.47 \times 10^{-9}$  g Ra/g slag. Slag/metal mass ratios were not reported, but assuming the mass slag/mass metal is 0.1, then the partitioning ratio (mass Ra in slag/mass Ra in metal) is  $>160$ .

#### E.5.22 Silver

As noted in Section E.2, silver will not react with FeO because  $Ag_2O$  is unstable at steelmaking temperatures. Silver has no solubility in liquid iron and thus the two metals will coexist as immiscible liquids (ASM 1993). Since silver has a significant vapor pressure (ca.  $10^{-2}$  atm at 1,816 K), some volatilization might be expected. Sappok et al. (1990) reported that induction melting of steel contaminated with silver resulted in the silver being primarily distributed to the metal, but some was detected both in the slag and in the offgas dust. However, the distribution was not quantified. Harvey (1990) concluded, based on the instability of  $Ag_2O$  and the expected similarity to the behavior of copper in steel, that silver "would be expected to remain in the melt under all normal steelmaking conditions."

Ag-110m activity was measured for two heats of stainless steel at Studsvik (Menon et al. 1990). The Ag-110m activity was distributed as follows:

- ingot ..... 290 kBq
- slag ..... 1.3 kBq
- baghouse dust ..... 93 kBq

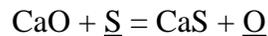
### E.5.23 Strontium

Strontium is predicted to partition to the slag. Nakamura and Fujiki (1993) studied the partitioning of Sr-85 during the air induction melting of ASTM-A335 steel in a 500-kg furnace with a slag basicity of 1. All of the Sr-85 was found in the slag (recovery was 75%). Larsen et al.(1985b) described the melting of three heats of Type 304L stainless weighing 500 to 700 lb each in an air induction furnace. The amount of strontium remaining in the ingots was 1% in two cases and zero in the third. Sr-85 was found in the slag and the baghouse dust but no mass balance was provided. Slagging practice was not documented other than to state that a small amount of a "slag coagulant" was added to aid in slag removal. Schuster and Haas melted St37-2 steel in a 5-kg laboratory furnace using a carborundum crucible. Lime, silica, and alumina were added as slag formers. The melt was allowed to solidify in situ. About 80% of the Sr-85 was found on the ingot surface, 6.3% in the slag, 0.5% in the ingot, and 0.02% in the aerosol filter. The material on the ingot surface would most likely have been found in the slag under more realistic production conditions.

Strontium can also react with sulfur and the resultant SrS should partition to the slag (Bronson and St. Pierre 1985).

### E.5.24 Sulfur

Sulfur is a generally undesirable element except in certain steels where higher sulfur levels are desired for free machining applications. As indicated at the beginning of this section, the maximum sulfur content of a typical low carbon steel is 0.05%. Sulfur is difficult to remove from the melt. One mechanism for sulfur removal is reaction with lime in the slag to form calcium sulfide according to the reaction:



This reaction is facilitated by constant removal of high basicity slag and agitation. According to Stubbles, the concentration ratio  $\frac{(\text{S})}{[\text{S}]}$  rarely exceeds 8 in EAF melting of steel (Stubbles 1984b).

Although sulfur has a very low boiling point (see Table E-3), the compounds it forms within the slag (e.g., CaS) are very stable at steelmaking temperatures.

Engh (1992) described the partitioning of sulfur between slag and metal as a function of slag acidity and FeO content of the slag. Assuming that the slag contained 25% FeO and 20% acid components ( $\text{SiO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{B}_2\text{O}_3$ , and  $\text{TiO}_2$ ), the ratio  $\frac{[\text{S}]}{[\text{S}]}$  would range between about 16 and 26.

#### E.5.25 Thorium

Based on the stability of  $\text{ThO}_2$ , thorium should partition to the melt. Harvey (1990) notes that the stability of  $\text{ThO}_2$  has been exploited by using the material in steel melting crucibles. However, because of their high specific gravity (9.86),  $\text{ThO}_2$  particles may settle in the melt and not reach the slag.

#### E.5.26 Uranium

Free energy calculations suggest that uranium should partition to the slag. Heshmatpour and Copeland (1981) conducted a number of small-scale partitioning experiments where 500 to 1,000 ppm of  $\text{UO}_2$  was added to 50 to 500 g of mild steel and melted in either an induction furnace or a resistance furnace. Slag and crucible composition were varied as well. With the use of highly fluid basic slags and induction melting, partition ratios (mass in slag:mass in metal) from 1.2:1 to >371:1 were obtained.

Larsen et al. (1985a) reported that, although uranium was not detected in the feed stock, it was sometimes found in the slag and in the baghouse dust. Schuster and Haas (1990) determined in small laboratory melts that when slag formers were added, the uranium content was reduced from 330  $\mu\text{g U/g Fe}$  to 5  $\mu\text{g U/g Fe}$ . Harvey (1990) commented that British Steel had occasionally used uranium as a trace element in steelmaking. Based on their experience, the uranium was absorbed in the slag in spite of the fact that  $\text{UO}_2$ , which has a density ( $10.9 \text{ g/cm}^3$ ) significantly higher than that of iron, could conceivably settle in the melt.

Abe et al. (1985) studied uranium decontamination of mild steel using small (100 g) melts in a laboratory furnace. Melting was done in an argon atmosphere at a pressure of 200 torrs in alumina crucibles with 10 wt% flux added to the charge. The uranium decontamination factor was found to be a function of the initial contamination level, varying from about 200 to about 5,000 as the uranium concentration increased from 10 to 1,000 ppm. Optimum decontamination occurred when the slag basicity was 1.5 with a  $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2$  slag. Decontamination was further enhanced by additions of  $\text{CaF}_2$  or  $\text{NiO}$  to the slag.

### E.5.27 Zinc

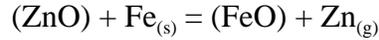
Zinc is not expected to react with the slag constituents and, because of its low boiling point, some fraction should evaporate from the melt. In fact, dust from steelmaking operations is an important secondary source of zinc. In 1990, about 100,000 tonnes of zinc were recovered from baghouse dust in Europe (Perrot et al. 1992). Hino et al. (1994) studied the evaporation of zinc from liquid iron at 1,873 K and found that the evaporation rate was first order with respect to the zinc content of the melt. The mass transfer coefficient in the liquid phase was estimated to be 0.032 cm/s.

Nakamura and Fujiki (1993) observed that, when induction melting both ASTM-A335 and SUS 304 steels, about 60% to 80% of added Zn-65 remained in the ingot. In one test with ASTM-A335 steel, 90.7% of the added zinc was recovered. Of the total amount recovered, about 14% was found in the offgas and 1% in the slag, with the balance remaining in the ingot. Sappok et al. (1990) reported that, in some instances, zinc was found only in the offgas collection system and, in another melting campaign, some zinc was found in the ingot and the slag as well as in the offgas system. The causes of these differences are not apparent.

On the other hand, Stubbles states that zinc is volatilized during EAF melting (Stubbles 1984a). Harvey (1990) supports the view of Stubbles noting that zinc is volatilized during melting and collected as ZnO in the baghouse filters. "The volatilization is very efficient, and the residual content of zinc in the steel is likely to be below 0.001%, whereas the zinc oxide content of the dust is often more than 10%."

Perrot et al. (1992) note that in spite of its low boiling point and expected ease of evaporation, zinc removal from liquid steel is far from complete. Industrial experience indicates that the zinc content is often above 0.1 wt.% in liquid cast iron at 1,573–1,673 K but is somewhat lower in liquid steel at 1,773–1,873 K. At 1,773 K, assuming that the zinc vapor pressure over the melt is 0.01 atmosphere, the calculated solubility of zinc in iron is about 72 ppm. The solubility of zinc in liquid iron is decreased by other solute elements with ion interaction coefficients greater than zero (e.g., Al and Si) and decreased by solutes with coefficients less than zero (e.g., manganese and nickel).

Richards and Thorne (1961) studied the activity of ZnO in slags with various CaO:SiO<sub>2</sub> ratios, over the temperature range 1,373 to 1,523 K, based on the assumption that the following slag/metal reaction controlled the equilibrium:



The parentheses indicate slag components, as usual. Further assuming that the gas phase contained 3 vol% Zn, they calculated that, at 1,473 K, the amount of zinc in the slag could be represented by the expression:

$$(\text{wt}\% \text{ Zn}) = \frac{0.022 (\text{wt}\% \text{ FeO}) (\gamma_{\text{FeO}})}{(\gamma_{\text{ZnO}})}$$

where all components of the equation involve the slag phase. For a fixed FeO concentration, the amount of zinc in the slag decreased with increasing temperature and increasing ratios of CaO:SiO<sub>2</sub>. For example, at 1,473 K, when the CaO:SiO<sub>2</sub> ratio was 0.3:1, the slag contained 1.2 wt% Zn and, when the CaO:SiO<sub>2</sub> ratio was 1.2:1, the zinc content of the slag had dropped to 0.8 wt%. If one extrapolates these results to 1,873 K, the amount of zinc in the slag would be only about 0.009%.

Menon et al. (1990) found that, during the melting of two stainless steel heats, the Zn-65 was about equally distributed between the melt and the baghouse dust.

From the available information it appears that, when the scrap metal charge has a reasonably high zinc content, significant amounts of zinc will be volatilized but, when the zinc levels in the charge are low, vaporization will be more difficult. Virtually no zinc should remain in the slag.

#### E.5.28 Zirconium

Based on free energy considerations, zirconium would be expected to partition to the slag. Stubbles' information for EAF steel melting supports this hypothesis (Stubbles 1984a).

## E.6 INFERRED PARTITIONING

No theoretical or experimental evidence exists for the partitioning of several elements that may be contaminants in steel. This section proposes the distribution of these nuclides based on chemical and/or physical behavior.

### E.6.1 Curium

Curium should behave like other elements in the actinide series such as americium and partition to the slag.

### E.6.2 Promethium

Promethium should behave like other rare-earth elements such as europium and samarium and partition to the slag.

## E.7 SUMMARY

In summarizing the distribution of the various potential contaminants that might be introduced into the steel melting process, one must define certain process parameters including:

- ratio of mass of steel produced to total mass of scrap charged to furnace ..... ( $R_1$ )
- ratio of mass of slag to mass of steel produced ..... ( $R_2$ )
- ratio of mass of baghouse dust to mass of steel produced ..... ( $R_3$ )
- fraction of baghouse dust from slag ..... (%Sl)
- fraction of baghouse dust from steel ..... (%St)

The following values were adopted for each of these process parameters:

- $R_1^{12}$  ..... 0.9

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<sup>12</sup> Pulliam (1996) stated that Bayou Steel typically produces 0.882 ton of steel billets per ton of scrap charged. When averaged over the total U.S. production, the process efficiency is much higher. According to the U.S. Geological Survey for the year 1994, the amount of recirculating home scrap was 132,300 tons, while 39.5 million tons of EAF steel were produced. Thus, the annual average ratio of home scrap to steel produced was 0.3% ( Fenton 1995). (Throughout this appendix, capacities of metal recycling facilities, and other parameters characterizing the metal refining industries will generally be cited in metric tons [tonnes] or, if English units were cited in the source documents, in short tons. The word "ton" will always mean short ton [1 ton = 0.9072 tonne]. )

• $R_2$ <sup>13</sup> .....	0.13
• $R_3$ <sup>14</sup> .....	15 kg/t of steel melted (16.5 to 18 kg per tonne of carbon steel produced in EAF) (A.D. Little 1993)
• %Sl <sup>15</sup> .....	33.3
• %St .....	66.7

The  $R_1$  value is based on the following assumptions:

- 5% of metal in each heat becomes home scrap, which is returned to the furnace in a later heat
- 1.5% of metal is lost to baghouse dust
- 2% of metal is lost to slag
- 1.5% is unaccounted for

Based on these process parameters and the information presented previously, the assumed distribution of the various elements is summarized in Table E-8. Since the amount of baghouse dust contributed by the melt is 5 kg/t, if a potential radioactive contaminant tended to concentrate in the melt, the dust would contain 1% of the activity in the melt. Similarly, since the amount of baghouse dust contributed by the slag is 5 kg/t of metal, and since the mass of the slag is  $\frac{1}{10}$  the mass of the melt, if such a contaminant tends to concentrate in the slag, 5% of the slag activity would be transported to the baghouse. For simplicity, the baghouse efficiency is assumed to be 100% in evaluating partition ratios.

Where varying results are presented by different investigators, emphasis was placed on results which represented EAF melting of carbon steel with basic slags.

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<sup>13</sup> According to R. West of International Mill Services, a major slag marketer, between 0.12 and 0.14 tons of slag are generated per ton of steel produced (West 1996). Since this appears to be a more realistic figure than the 10% cited in Stubbles 1984a, the average of 0.13 was adopted for the present analysis.

<sup>14</sup> Additional information on baghouse dust is included in Appendix E-2.

<sup>15</sup> Based on the baghouse dust composition reported by SAIC (McKenzie-Carter et al. 1985), adjusted for the ZnO content, and assuming that all the  $Fe_2O_3$  and one-half the MnO and  $SiO_2$  are from the melt, the %Sl is 33%.

Table E-8. Proposed Distribution of Potential Contaminants During Carbon Steelmaking

Element	Distribution (%)				Comments
	Melt	Slag	Baghouse	Atmosphere	
Ac		95	5		
Ag	99/75		1/25		
Am		95	5		
Ba		95	5		
Bi			100		Assumed same as Pb
C	100/27			0/73	Depends on melting practice
Ca		95	5		
Cd			100		
Ce		95	5		
Cl		50	50		Some Cl in baghouse dust (McKenzie-Carter et al. 1985)
Cm		95	5		
Co	99		1		
Cr	99/40	0/57	1/3		Longest-lived isotope: $t_{1/2} = 27.7$ d
Cs		0/5	100/95		
Cu	99		1		Longest-lived isotope: $t_{1/2} = 2.58$ d
Eu		95	5		
Fe	97	2	1		
H	10			90	Needs further analysis
I				100	
Ir	99		1		
K		50	50		Needs further analysis
Mn	24/65	72/32	4/3		
Mo	99		1		
Na		50	50		Needs further analysis
Nb		95	5		
Ni	99		1		
Np		95	5		
P	9	87	4		Longest-lived isotope: $t_{1/2} = 25.3$ d
Pa		95	5		
Pb			100		
Pm		95	5		

Table E-8 (continued)

Element	Distribution (%)				Comments
	Melt	Slag	Baghouse	Atmosphere	
Po			100		
Pu		95	5		
Ra		95	5		
Re	99		1		
Rn				100	
Ru	99		1		
S	19	77	4		Slag % is max. expected. Melt % may be higher. (Maximum $t_{1/2} = 87.2$ d.)
Sb	99/80		1/20		Conflicting reports on Sb distribution
Se	19	77	4		Assumed to behave like S
Sm		95	5		
Sr		95	5		
Tc	99		1		
Th		95	5		
U		95	5		
Y		95	5		
Zn	20/0		80/100		Zn difficult to remove from melt at low concentrations
Zr		95	5		

Additional factors which may alter the results presented in Table E-8 are presented below.

- In some cases, results are quoted for stainless steels rather than carbon steels. The thermodynamic activity of solutes in the highly alloyed steel melt should be different from that in plain carbon steels and the slag chemistry will be significantly altered.
- Perspective on kinetically driven processes may be altered by the scale of the melting operation.
- Melt temperatures and holding times in the molten state may be quite different in cited experiments as compared to commercial practice. This can significantly impact conclusions, especially with regard to volatile elements. The mass concentrations of potential contaminants in free-released steel scrap would be quite low. Consequently, some of the partition predictions made here may be overridden by other factors. For example, if evaporation kinetics of volatile elements control the release, small quantities

of zinc may remain in the steel. For strong oxide formers which should partition to the slag, transfer may be impeded due to the high density of many of the actinide and rare-earth oxides. The experimental evidence of this possibility is mixed. For example,  $\text{Eu}_x\text{O}_y$  seems to be removed from the melt during normal EAF melting, but  $\text{CeO}_2$  may not be completely removed. One investigator reported that the uranium decontamination factor in mild steel increased with increasing contaminant levels (Abe et al. 1985).

In addition, the expected partitioning may be altered significantly if the melting practice is changed. Examples presented in this appendix include the removal of niobium from the slag to the melt and movement of tungsten in the opposite direction.

The information in Table E-8 does not explicitly consider home scrap or contaminated furnace refractories. Home scrap (i.e., the scrap from the melting process that is recirculated into future furnace charges) should have the same contaminant distribution as the melt from which it was produced. The contamination of furnace refractories was not studied in the present analysis. However, it should be noted that residuals remaining in the furnace from a melt are frequently recovered in the next one to two melts. For example, when melting a low alloy steel containing, say, 1% Cr, the following heat or two will contain more chromium than would be expected if the only source were the furnace charge for the ensuing heats (Stubbles 1996).

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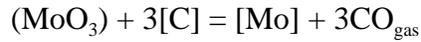
**APPENDIX E-1**

**EXTENDED ABSTRACTS OF SELECTED REFERENCES**

Chen W. et al. 1993. "Reduction Kinetics of Molybdenum in Slag." *Steel Research* 63 (10): 495-500.

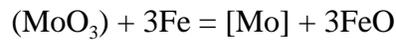
Reduction of molybdenum oxide in slag over an iron-carbon melt is completed in 5 min in 1-kg lab melts.

The reaction may be:



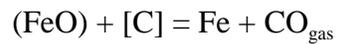
$$\Delta F^\circ = 82.35 - 0.2370T \text{ [kJ]}$$

or a two-step process



$$\Delta F^\circ = -213.6 + 0.0386T \text{ [kJ]}$$

and



$$\Delta F^\circ = 98.65 - 0.0919T \text{ [kJ]}$$

At 1,440 to 1,500°C the reaction rate is controlled by molybdenum diffusion in slag and, from 1,500 to 1,590°C, the reaction rate is controlled by molybdenum diffusion in the melt.

Gomer, C. R., and J. T. Lambley. 1985. "Melting of Contaminated Steel Scrap Arising in the Dismantling of Nuclear Power Plants," Contract No. DED-002-UK, Final Report. British Steel Corporation, for Commission of the European Communities.

This paper discusses the same tests but in somewhat greater detail than Pflugard et al. (1985). The EAF slag is about 5% to 10% of the metal cast weight and involves chiefly additions of carbon, lime and ferrosilicon plus eroded refractories and general oxidation products. Melts were about 2.5 t each. In the arc furnace melt with a CsCl addition, cesium was added with melt charge and, since CsCl is volatile below steelmaking temperature, the CsCl volatilized before any could be incorporated into non-reactive basic slag. In an induction furnace test, *CsOH was added into liquid steel pool with complete cover of relatively cool, quiescent acid slag.* In an arc furnace test with CsOH, cesium was added to the molten pool but slag conditions are not described nor is the hold time after addition stated. However, Gomer stated that, although the slag was made as acidic as the furnace liner could withstand, it still did not contain enough silica to fix the cesium as cesium silicate. The limited cesium recovery of only 50% was attributed to cesium condensation on cooler duct walls upstream of sampling point. In an arc furnace test with Cs<sub>2</sub>SO<sub>4</sub>, cesium was added as in the previous arc furnace test with CsOH. The higher cesium recovery in the slag is attributed to incorporation of Cs<sub>2</sub>SO<sub>4</sub> into the slag.

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Larsen, M. M., et al. 1985a. "Sizing and Melting Development Activities Using Contaminated Metal at the Waste Experimental Reduction Facility," EGG-2411. EG&G Idaho, Inc.

This report describes melting of contaminated carbon steel from the SPERT III reactor in a 1,500-lb coreless induction furnace at the Waste Experimental Reduction Facility (WERF). Six heats were thoroughly sampled. All showed only Co-60 in feed stock. However, due to concentrating effects, Eu, Cs, and occasionally U were found in the slag, while the baghouse dust contained Co, Cs, Eu, and U, and spark arrestor dust contained Co and Eu. This occurred even though, except for Co-60, all these nuclides were not seen in the feed at the limits of detection. Molten metal samples either contained Co-60 or emitted no detectable radiation.

Detectable quantities of Co-60 were seen in slag and baghouse and spark arrestor dust. Of 35,900 Ci of Co-60 charged into six melts, 1,361 Ci were recovered in the baghouse and spark arrestor dust (3.8%).

Larsen, M. M., et al. 1985b. "Spiked Melt Tests at the Waste Experimental Reduction Facility," PG-Am-85-005. Idaho National Engineering Laboratory, EG&G Idaho, Inc.

Tracer tests were conducted at WERF in a 1,500-lb induction furnace using Type 304L stainless steel. Three heats, weighing 474 to 689 pounds each, were made. All were doped with Co-60, Cs-137 and Sr-85, while Ir-192 was added to only one. Melt temperatures were not specified; slag chemistry was not specified but apparently no slag formers were added<sup>16</sup>. A small amount of slag "coagulant" was added to aid in slag removal. Tracers were added to the initial furnace charge.

The fraction of each radionuclide partitioning to the metal was determined on the basis of *melt* samples, as listed in Table E1-1. Subsequent analysis of the *ingots* suggested that these analyses were biased low because of the large sample sizes taken from the melts which caused self-shielding. Averaged results from ingot tests (percent of activity in ingot), also listed in Table E1-1, are believed to be more reliable. The last column lists the fraction of the charge recovered in the ingot in each test.

Table E1-1. Distribution of Radionuclides in Tracer Tests at WERF (%)

Test No.	Co-60		Sr-85		Cs-137		Ir-192		Ingot fraction
	melt	ingot	melt	ingot	melt	ingot	melt	ingot	
1	87	96	1.7	1	1.3	10	—	—	93
2	73	96	2.3	0	1.8	8	—	—	98.4
3	77	97	2.3	1	1.8	5	57	60	95.4

Some problems were encountered with entrained metal in the slag samples. Poor results were obtained on activity measurements of slag and baghouse dust; consequently, no activity balance was calculated.

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<sup>16</sup> A subsequent publication reported that the composition of the slag was 72% SiO<sub>2</sub>, 13% Al<sub>2</sub>O<sub>3</sub>, 4.5% Na<sub>2</sub>O, 5.0% K<sub>2</sub>O and 0.7% CaO (Worchester et al. 1993).

Menon, S., G. Hernborg, and L. Andersson. 1990. "Melting of Low-Level Contaminated Steels." In *Decommissioning of Nuclear Installations*. Elsevier Applied Science.

Studsvik AB in Sweden has a 3-t induction melting furnace where low-level radioactive scrap is remelted. Based on the melting of 33.61 t of carbon steel, the weight of ingots was 32.27 t, the weight of slag was 1.32 t and the weight of dust was 0.019 t. No Cs-137 was measured in the ingots and the activity levels in the slag were also below the measurement threshold for the detection equipment. Dust contained the following nuclides:

- Co-60 ..... 1,300 Bq/kg
- Zn-65 ..... 14,400 Bq/kg
- Cs-137 ..... 21,800 Bq/kg

Menon et al. also reported on the results of two stainless steel melts weighing a total of 5,409 kg. The weight of slag in melt 92 was 1.1% of the total and in melt 93 it was 0.5%. The weight of dust from the combined melts was 2.49 kg. Activity measurements are listed in Table E1-2.

Table E1-2. Specific Activities of Ingots and Slags (Bq/kg)

Melt No.	Material	Co-58/Co-60	Mn-54	Cs-134/Cs-137	Ag-110m	Sb-125	Zn-65
92	ingot	1350	8.2		54	29	34
	slag	720	73	2320	30		
93	ingot	3440				50	
	slag	207	10	1493			
Baghouse dust		264/31,200	146	1,125/134,650	37,450	670	52,250

Meraikib, M. 1993. "Manganese Distribution Between a Slag and a Bath of Molten Sponge Iron and Scrap." *ISIJ International* 33 (3): 352-360.

The manganese distribution ratio is given by the expression:

$$\begin{aligned}\eta_{\text{Mn}} &= \frac{(\text{Mn})}{[\text{Mn}]} \\ &= a_{[\text{O}]} f_{[\text{Mn}]} \exp\left(\frac{27005}{T} - 7.2324\right)\end{aligned}$$

for a temperature range of 1,550 to 1,670°C. This equation is based on 80 metal samples from melts in a 70-ton EAF, and reflects Meraikib's finding a limited influence of slag basicity on the manganese distribution ratio. A different expression, explicitly including the influence of basicity, was presented in Section E.5.14.

Extensive thermodynamic calculations are included.

Nakamura, H., and K. Fujiki. 1993. "Radioactive Metal Melting Test at Japan Atomic Energy Research Institute."

Air melting was accomplished in a high frequency (1,000 Hz) induction furnace of 500 kg capacity. Researchers studied the effects of melting temperature, slag basicity and type of steel (ASTM-A335 and SUS 304) on partitioning using radioactive tracers: Mn-54, Co-60, Sr-85, Zn-65 and Cs-137. The slag basicity ( $\text{CaO}/\text{SiO}_2$ ) was 1 for A335 and 3 for SUS 304. Five radioactive tracer heats (three ASTM-A335 and two SUS 304) and six JPDR decommissioning heats were produced. The average material balance was 99.5%, with the maximum difference being 3%. Material distribution was: 95% ingot, 2-3% slag, 0.1% dust, 1-2% other (metal on tundish and metal splash). The melt temperature was 1,873 K. Results from one of the three A335 tracer tests are as follows:

- Mn-54: recovery 98%, about 7% of which was in slag, balance in *ingot* (approximate Mn content of other three ingots was 90%)
- Co-60: 99.5% recovery, all in ingot
- Zn-65: 90.7% recovery, about 14% of which was in exhaust gas, 1% in slag and balance in ingot
- Sr-85: 72.7% recovery, 100% in slag
- Cs-137: 77% recovery, 50% of which was in slag and 50% in exhaust gas

The other four tracer tests showed similar tendencies.

The melt was held at temperature for about 20 minutes after tracers were added before casting the ingot. Tracers were not present in initial melt charge, but rather were added after melting was completed and the desired temperature of 1,873 K was reached. Exhaust gas analyses were based on sampling about 0.04% of total exhausted volume.

Ostrovski, O. 1994. "Remelting of Scrap Containing Tungsten and Nickel in the Electric Arc Furnace." *Steel Research* 65 (10): 429-432.

This paper discusses partitioning of tungsten between slag and melt during melting of tungsten-bearing steel scrap in a 25-t EAF with slags of varying basicity. Melting under strongly oxidizing conditions (30 min. oxygen blow) and high CaO/SiO<sub>2</sub> ratio resulted in 94% of the tungsten in slag, 4% in metal and 2% lost. Thermodynamic equations for calculating the partition ratio are provided.

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Pflugard, K., C. R. Gomer, and M. Sappok. 1985. "Treatment of Steel Waste Coming From Decommissioning of Nuclear Installations by Melting." In *Proceedings of the International Nuclear Reactor Decommissioning Planning Conference*, NUREG/CP-0068, 349-371. Bethesda, MD.

Sappok described nine melts totaling 24 t (plus starting blocks, i.e., furnace heel) in 10-t and 20-t induction furnaces. Mass balance: 28,000 kg steel, 800 kg slag, 20 kg furnace lining, and 64 kg cyclone and baghouse dust. Co-60 and Cs-137 distributions were:

Co-60: 97% in steel, 1.5% in slag, 1.5% in cyclone and baghouse

Cs-137: 90% in slag, 1% in furnace lining, (5% in baghouse tubes and dust).

Activities accounted for: Co-60–96%; Cs-137–73%.

No discussion of slagging practices or melting practices and temperatures was included.

Gomer used a 500 kg high frequency induction furnace, a 5-t EAF and a 3-t BOF (no results reported). Non-quantitative tests from two 5-t arc furnace melts showed that all the Co-60 was reported in the melt; quantities in slag and fume were below detection limits. Traces of Am-241 were found in slag when melting contaminated heat exchanger tubing in the arc furnace. The results of three quantitative tests of cesium in 5-t EAF's and one in a 500 kg induction furnace are listed in Table E-6 of the present report.

Gomer notes that cesium stays in slag in an induction furnace and can be made to stay largely in slag in an arc furnace but conditions "may not be fully practical in production furnaces." No information on melting and slagging practice is included.

Sappok, M., et al. 1990. "Melting of Radioactive Metal Scrap from Nuclear Installations." In *Decommissioning of Nuclear Installations*, 482-493. Elsevier Applied Science.

Melting to date has totaled 2,000 tons of steel (steel presumed from Pflugard et al., but not so stated in report) in a 20-ton induction furnace. (A new dedicated facility with a 3.2-ton medium frequency induction furnace had recently been completed but no radioactive scrap had yet been melted in the new equipment). When melting zinc-plated metal, zinc is "found in the filter dust." Typical mass balance: 98.6% metal, 1.2% slag and 0.2% filter dust.

For the melting period May 17, 1985: Ce-144 all in slag, Zn-65 all in offgas, Mn-54 distributed between slag and offgas, Cs-134/137 distributed between slag and offgas, Co-60 mostly in melt but some in slag and some in offgas (Co-60 is only the radionuclide detected in the melt).

For the melting period September 27-28, 1985: Mn-54 distributed between slag and offgas; Zn-65 all in offgas; Eu-154 all in slag; Ag-110m distributed among metal, slag and offgas; Cs-134/137 distributed between slag and offgas; Co-60 distributed among melt, slag and offgas, but mostly in the melt.

For the melting period January 1, 1986 – March 14, 1986 (200 t): Cs-134/137 distributed between slag and offgas; Mn-54 distributed between slag and offgas; Zn-65 distributed among slag, metal and offgas; Ag-110m distributed among slag, metal and offgas, but mostly in metal; Co-60 distributed among slag, metal and offgas, but retained mostly in metal.

No discussion of slagging or melting practice was included.

Schuster, E., and E. W. Haas. 1990. "Behavior of Difficult to Measure Radionuclides in the Melting of Steel." In *Decommissioning of Nuclear Installations*. Elsevier Applied Science.

Laboratory melts were made using a Nernst-Tammann high-temperature furnace with temperatures to 1,700°C and a 3- to 5-kg melt size. Melt additions included: (1) electro-deposited Co-60, Fe-55 and Am-241 on steel disks, (2) carbonate or hydroxide precipitates or elemental carbon on SiO<sub>2</sub> filters, (3) direct insertion of uranium and UO<sub>2</sub>. The melts were allowed to solidify in the carborundum tube crucible. About 60% to 80% of the slag was recovered when melting St37-2 steel under Ar + 10% H<sub>2</sub>. The results are presented in Table E1-3.

Table E1-3. Distribution of Radionuclides Following Laboratory Melts

Sample Location	Percentage of Nuclide in Each Medium			
	Co-60	Fe-55	Ni-63	C-14
Ingot	108	70	≈ 82	91
Slag	0.2	n.d.	0.04	0.4
Aerosol Filter	0.2	n.d.	0.06	< 0.001

In a test for strontium distribution where slag-forming oxides CaO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> were added, the Sr-85 distribution was: surface layer of ingot—ca. 80%, slag—6.3%, ingot—0.5%, aerosol filter—0.02%. In a test with Am-241, the isotope distribution was: ingot—1%, slag—110% and aerosol filter—0.05%. In tests with UO<sub>2</sub>, when slag formers were added, the uranium concentration in the ingot was reduced from 330 to 5 ppm.

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Starkey, R. H., et al. 1961. "Health Aspects of the Commercial Melting of Radium Contaminated Ferrous Metal Scrap." *Industrial Hygiene Journal* 489-493.

Melting of 40 tons of radium-contaminated steel scrap blended with 20 tons of uranium-contaminated steel scrap in an EAF is discussed. Based on eight heats, the average concentration of radium in steel ingots was  $<9 \times 10^{-11}$  g of Ra per g of steel, and the radium content of slag was  $1.47 \times 10^{-9}$  g Ra per g of slag. No information on melting and slagging conditions was provided.

Stubbles, J. R. 1984a. "Tonnage Maximization of Electric Arc Furnace Steel Production: The Role of Chemistry in Optimizing Electric Furnace Productivity - Part V." *Iron and Steelmaking* 11 (6): 50-51.

Stubbles notes that recovery (from scrap) of Cb, B, Ti, Zr, V, Al, and Si in steel is zero and recovery of Mo, Ni, Sn, and Cu is 100%. Pb, Zn, and Sb are volatilized. Cr and Mn are distributed between slag and metal based on the degree of slag oxidation (the "FeO" level). Chromium recovery ranges from about 30% to 50% and manganese recovery from about 10% to 25%. No supporting information is provided for these recovery values. According to Stubbles, lead from babbitts, batteries, etc. melts and quickly sinks to the furnace bottom, often penetrating the refractory lining. However, when leaded scrap is added to liquid steel, the lead will go into solution and boil off like zinc, exiting with the fume.

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Stubbles, J. R. 1984b. "Tonnage Maximization of Electric Arc Furnace Steel Production: The Role of Chemistry in Optimizing Electric Furnace Productivity - Part VII." *Iron and Steelmaking* 11 (8): 46-49.

Stubbles cites the following charge to produce one ton of liquid steel:

metals .....	2,100 lb
flux .....	40 lb
gunning material (high MgO) .....	10 lb
charge carbon .....	10 lb

In this example, the initial slag volume is 100 lb per ton (see Note 12 on p. E-33). Most input sulfur remains in metal and is extremely difficult to transfer to slag. The theoretical sulfur distribution  $\frac{[S]}{[S]}$  rarely exceeds 8 in EAF's. Working down sulfur during melting requires constant removal of high basicity slag plus agitation.

One reason for adding excess carbon above the desired final level is to use decarb oxygen from a lance to promote slag/metal reactions and help boil out hydrogen. Hydrogen levels on the order of 1 ppm can be obtained after a 15-minute carbon boil where the rate of carbon removal is 1%/hr. If the carbon removal rate is 0.1%/hr, the comparable hydrogen level is about 5 ppm (based on an initial level of 9 ppm).

**APPENDIX E-2**

**COMPOSITION OF BAGHOUSE DUST**

## COMPOSITION OF BAGHOUSE DUST

Various studies have reported measurements of the composition of baghouse dust. Results of measurements reviewed in this study are reported here.

Babcock and Wilcox Company (Kaercher and Sensenbough 1974) provided the baghouse dust composition at its No. 3 EAF melt shop at Koppel, Pa. The melt shop included one 50-ton, one 75-ton and three 100-ton furnaces used for the production of carbon, alloy and stainless steels.

The dust composition (in wt%) was:

Fe <sub>2</sub> O <sub>3</sub> .....	52.7
CaO .....	13.6
Al <sub>2</sub> O <sub>3</sub> .....	0.9
SiO <sub>2</sub> .....	0.9
MgO .....	12.6
Mn <sub>2</sub> O <sub>3</sub> .....	0.6
ZnO .....	6.3
NiO .....	0.1
Cr <sub>2</sub> O <sub>3</sub> .....	0.6
CuO .....	0.1
Loss on ignition at 1100°C .....	6.8
Balance .....	4.6

The average dust collection was 12 lb per ton of steel melted. More recently, dust collection has been increasing, reaching a level of 26 lb per ton of carbon steel melting capacity in 1985 and 30 lb per ton of carbon steel melting capacity in 1992 (A. D. Little 1993).

Arthur D. Little (ADL) (1993) prepared a survey on EAF dust generation for the Electric Power Research Institute in 1993 based on 52 shops which melted carbon steel. ADL estimated that about 600,000 tons of dust were generated in 1992 from U.S. carbon steel operations. The dust composition (in wt%) was:

Fe .....	28.5
Zn .....	19.
Cd .....	< 0.01
Pb .....	2.1
CrO .....	0.39
CaO + MgO .....	10.7

The high levels of zinc in the dust are the result of large amounts of galvanized steel in the furnace charge. According to ADL, the disposition of the baghouse dust in 1992 was:

- Disposal to landfill ..... 1.2%
- Shipped to fertilizer ..... 2.3%
- Shipped to zinc recovery ..... 86.5%
- Miscellaneous, delisted ..... 0.1%

Lehigh University (1982) conducted a study on EAF dust for the Department of Commerce in 1982. Dust composition from stainless steel and carbon steel melts is shown in Table E2-1.

Table E2-1. Composition of Baghouse Dust (wt%)

Component	Stainless Steel Dust	Carbon Steel Dust
Fe	31.7	35.1
Zn	1.0	15.4
Cd	0.16	0.028
Pb	1.1	1.5
Cr	10.2	0.38
CaO	3.1	4.8

McKenzie-Carter et al. (1995) described the composition of EAF dust taken from an earlier work by Brough and Carter (1972). The dust composition (in wt%) as quoted by Brough and Carter and interpreted by McKenzie-Carter et al. is:

Fe <sub>2</sub> O <sub>3</sub> .....	52.5
ZnO .....	16.3
CaO .....	14.4
MnO .....	4.4
SiO <sub>2</sub> .....	2.6
MgO .....	1.9
Na <sub>2</sub> O .....	1.5
Cl <sub>2</sub> .....	1.2
Other .....	5.2

Based on the original source, Cl<sub>2</sub> should be Cl<sup>-</sup> and 4.4% of "Other" is ignition loss. The dust was a by-product of melting low alloy carbon steels.

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- Lehigh University. 1982. "Characterization, Recovery, and Recycling of Electric Arc Furnace Dust." Sponsored by U.S. Department of Commerce.
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## **APPENDIX F**

### **DISTRIBUTION OF CONTAMINANTS DURING MELTING OF CAST IRON**

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## **DISTRIBUTION OF CONTAMINANTS DURING MELTING OF CAST IRON**

This appendix discusses the expected partitioning of contaminants during the production of cast iron. The approach taken here is to use the information developed for partitioning during the melting of carbon steel in electric arc furnaces (EAFs) presented in Appendix E, and by analogy predict the expected behavior of selected trace elements during the production of cast iron. To the extent possible, the deductive process takes into account differences in melting and slagging practice. This discussion should be viewed as a supplement to the information developed in Appendix E. Many of the same references are used as information sources and the detailed thermodynamic discussion is not repeated here.

In order to assess radiation exposures to products made of potentially contaminated cast iron, it is necessary to estimate the partitioning to cast iron of the elements listed in Table 6-3. The present discussion of partitioning during the production of cast iron therefore includes these elements.

### **F.1 BACKGROUND**

Cast iron is an alloy of iron and carbon (ca. 2 to 4.4 wt%) which also typically contains silicon, manganese, sulfur, and phosphorous. The high carbon content of the alloy results in a hard, brittle product which is not amenable to metalworking (as is steel); hence the alloy is cast into the desired end-use form. As noted by the United States Steel Corporation, now USX, (U.S. Steel 1951):

Castings are of innumerable kinds and uses, roughly grouped as chilled-iron castings, gray-iron castings, alloyed-iron casting, and malleable castings. In general, castings are made by mixing and melting together different grades of pig iron; different grades of pig iron and foundry scrap; different grades of pig iron, foundry scrap, and steel scrap; different grades of pig iron, foundry scrap, steel scrap and ferroalloys, and other metals.

Representative chemical compositions of cast iron are presented in Table F-1.

Cast iron is usually melted in a cupola furnace, an EAF, an electric induction furnace, or an air (reverberatory) furnace. A flow diagram for a typical iron foundry is shown in Figure F-1. The cupola is similar to a small blast furnace where the iron ore in the charge is replaced by pig iron and steel scrap. As described in U.S. Steel 1951:

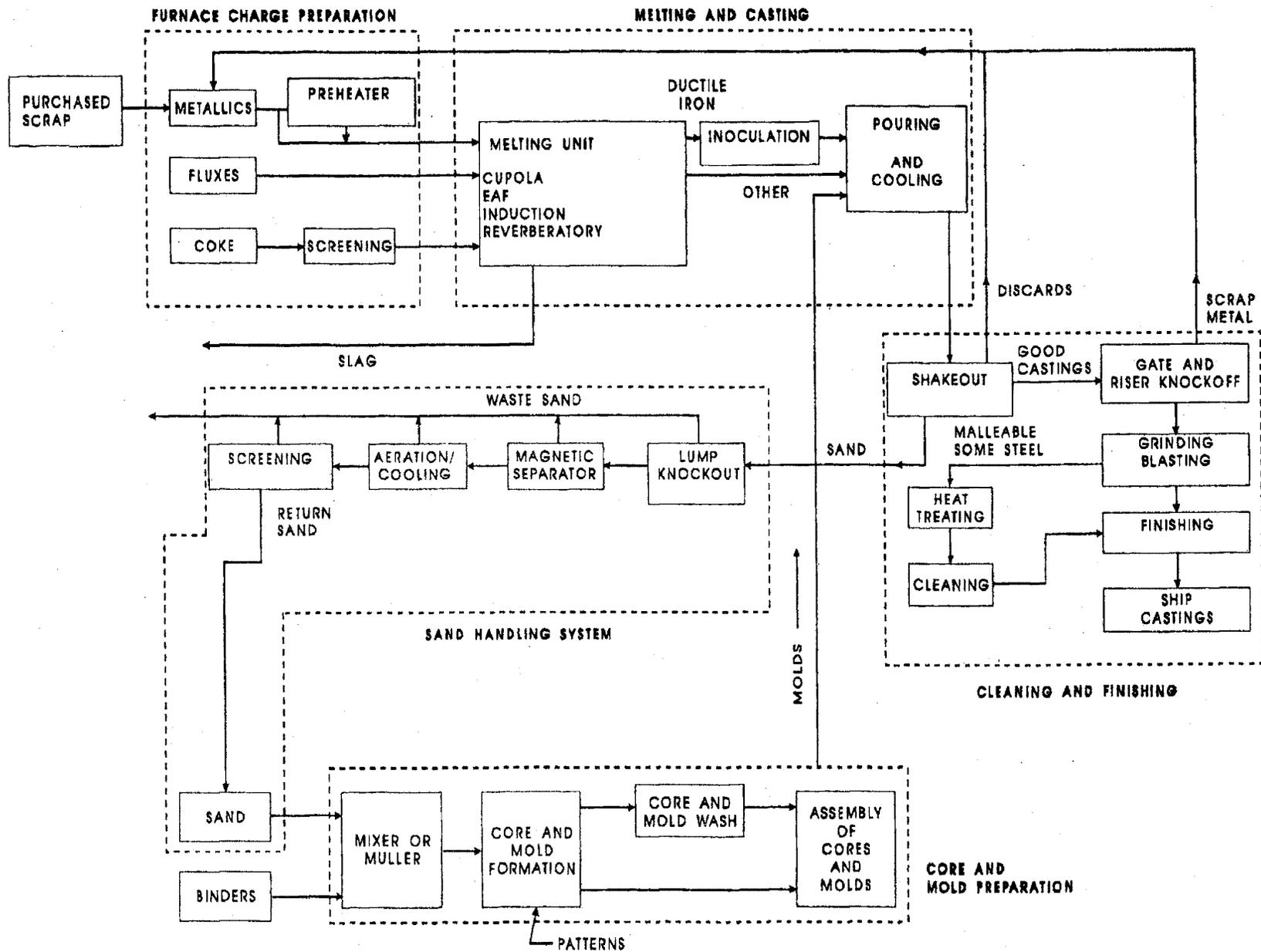


Figure F-1. Flow Diagram of a Typical Cast Iron Foundry (from U.S. EPA 1995)

The charge is composed of coke, steel scrap, and pig iron in alternate layers of metal and coke. Sufficient limestone is added to flux the ash from the coke and form the slag. The ratio of coke to metallics varies depending on the melting point of the metallic charge. Ordinarily, the coke will be about 8 to 10% of the weight of the metallic charge. It is kept as low as possible for the sake of economy and to exclude sulfur and some phosphorus absorption by the metal.

During melting, the coke burns as air is introduced at a 10 to 20 ounce (~0.4 - 0.8 kPa) pressure through the furnace tuyeres. During melting some of the manganese combines with the sulfur forming MnS which goes into the slag. Some manganese and silicon are oxidized by the air blast; the loss is proportional to the amount initially present. Carbon may be increased or reduced depending on the initial amount present in the metallic charge. It may be increased by absorption from the coke or oxidized by the blast. Phosphorus is little affected but sulfur is absorbed from the coke. Prior to casting, the slag is removed from the slag-off hole which is located just below the tuyeres. The molten metal is then tapped through a hole located at the bottom level of the furnace. The depth between these two tapping holes and the inside diameter of the furnace governs the capacity of the cupola (U.S. Steel 1951).

Table F-1. Chemical Composition of Ferrous Castings (wt%)

Element	Gray Iron	Malleable Iron (as white iron)	Ductile Iron	Steel Scrap <sup>a</sup>
C	2.0 - 4.0	1.8 - 3.6	3.0 - 4.0	0.18 - 0.23
Mn	0.40 - 1.0	0.25 - 0.80	0.5 - 0.8	0.60 - 0.90
P	0.05 - 1.0	0.06 - 0.18	< 0.15	≤ 0.40
Si	1.0 - 3.0	0.5 - 1.9	1.4 - 2.0	—
S	0.05 - 0.25	0.06 - 0.20	< 0.12	≤ 0.05

Source: U.S. EPA 1995

<sup>a</sup> Nominal composition of a low carbon steel (e.g., SAE 1020)

The melting temperatures used in producing cast irons are lower than those used in steel making. The melting point of pure iron is 1,538°C (1,711 K), while steel making temperatures are typically about 1,600°C (1,873 K). Furthermore, carbon depresses the melting point of iron: the melting point of an iron alloy containing 3.56% C and 2.40% Si is 1,250°C (1,523 K), while one containing 4.40% C and 0.6% Si has a melting point of 1,088°C (1,361 K) (U.S. Steel 1951).

Fluxing agents added to the furnace charge to promote slag formation include carbonates (e.g., limestone and dolomite), fluorides (e.g., fluorspar), and carbides (e.g., calcium carbide) (U.S.

EPA 1995). Obviously, the furnace environment during the production of cast iron is more highly reducing than that in typical steel melting.

Emissions from the cast iron melting furnaces include particulate matter, CO, SO<sub>2</sub>, and small quantities of chlorides and fluorides. These emissions are from incomplete combustion of carbon additives, oxidation of sulfur in coke (for cupola melting), flux additions, and dirt and scale in the scrap charge (U.S. EPA 1995). Melting of ductile iron requires the addition of inoculants such as magnesium in the final stages of melting. The magnesium addition to the molten bath results in a violent reaction and the production of MgO particulates and metallic fumes. Most of these emissions are captured by the emission control system and routed to the baghouse, where the fumes are cooled and filtered. Cupolas are also equipped with an afterburner in the furnace stack to oxidize the carbon monoxide and burn any organics.

In 1998, U.S. shipments of iron and steel castings were (Fenton 1999):

- Ductile iron castings ..... 4,070,000 t
- Gray iron castings ..... 5,460,000 t
- Malleable iron castings ..... 292,000 t
- Steel castings .. ..... 1,200,000 t
- Steel investment castings .....83,000 t
- Total ..... 11,100,000 t

Scrap consumption by manufacturers of steel castings and by iron foundries and miscellaneous users in that year is summarized below (Fenton 1998 ):

- Electric arc furnace ..... 7,600,000 t
- Cupola furnace ..... 7,500,000 t
- Air furnaces and other ..... 3,000 t
- Total ..... 15,100,000 t

Of this total, 5,800,000 t was home scrap.

In addition, 1,200,000 metric tons (t) of pig iron and 12,000 t of direct-reduced iron were consumed by the iron and steel foundries. The total metal consumption in 1998 was

16,300,000 t, which is about 47% greater than cast iron and steel shipments. This difference may be due to generation of home scrap. From a recycling perspective, a significant observation is that cast iron contains more than 90% scrap metal.

In 1989, about half of all iron castings were used by automotive and truck manufacturing companies and half of all ductile iron castings were used in pressure pipe and fittings (U.S. EPA 1995).

## F.2 MATERIAL BALANCE

Using the results of several studies, EPA (1995) has compiled emission factors for uncontrolled emissions from two types of gray iron foundries:

- Cupola furnace ..... 13.8 lb/ton<sup>1</sup> metal
- Electric arc furnace ..... 12.0 lb/ton metal

### F.2.1 Cupola Furnaces

Based on a 1980 EPA-sponsored environmental assessment of the iron casting industry, Baldwin (1980) reported that a typical cupola producing a medium-strength cast iron from a cold charge would utilize the following materials (as a percentage of iron input):

- Scrap steel ..... 48%
- Foundry returns (i.e., foundry home scrap) ..... 52%
- Ferrosilicon ..... 1.1%
- Ferromanganese ..... 0.2%
- Coke ..... 14%
- Limestone ..... 3%
- Melting loss ..... 2%

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<sup>1</sup> Throughout this appendix, capacities of metal recycling facilities, and other parameters characterizing the metal refining industries will generally be cited in metric tons (tonnes) or, if English units were cited in the source documents, in short tons. The word “ton” will always mean short ton (1 ton = 0.9072 tonne). When practicable, the metric equivalent will also be listed.

Baldwin also documented the quantities of material produced for three foundries: a malleable iron foundry using a induction furnace, a ductile iron foundry using a cupola, and a gray and ductile iron foundry using a cupola for primary melting which duplexes into induction furnaces. The amounts of byproducts are listed in Table F-2.

Table F-2. Amounts of Byproducts from Various Foundries

Byproduct	Amount Generated (lb per ton of metal melted)		
	Malleable Iron	Ductile Iron	Gray and Ductile Iron
Slag	34.5	173	130
Dust Collector Discharge	7.19		78.6

### F.2.2 Electric Arc Furnaces

According to a study conducted for EPA, a typical charge for an electric arc furnace (EAF) includes (Jeffery 1986):

- 50% ..... 60% scrap iron
- 37% ..... 45% scrap steel
- 0.5% ..... 1.1% silicon
- 1.3% ..... 1.7% carbon raisers<sup>2</sup>

Arc furnaces for cast iron melting range from 500-pound to 65-ton capacity, 25 tons being a common size (Baldwin 1980). According to Jeffery (1986), 94% to 98% of the EAF charge is recovered as iron.

### F.2.3 Chemistry Adjustments

As noted in Section F.2.1 and F.2.2, the furnace charge typically contains about 45% steel scrap. If this scrap were similar to that listed in the last column of Table F-1, then, to achieve the cast iron chemistries indicated in that table, it would be necessary to add carbon, phosphorous, sulfur, silicon, and possibly manganese to the furnace charge.

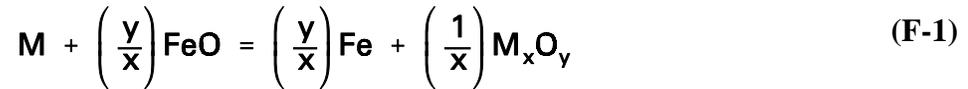
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<sup>2</sup> Carbon raisers are additives introduced into the bath to increase the carbon content of the cast iron, if required.

Production of ductile iron requires making additions to the melt which alter the shape of the graphite particles in the cast iron from flakes to a spheroidal form. Typically, the melt is inoculated with magnesium just before pouring to produce the ductile iron. Much of the magnesium boils off in the process. Sometimes barium, calcium, cerium, neodymium, praseodymium, strontium, and zirconium are also added as inoculants (Baldwin 1980). To reduce the costs of adding magnesium in larger ductile iron production operations, the melt is desulfurized before magnesium is added. This is frequently done by adding  $\text{CaC}_2$  (Baldwin 1980).

### F.3 PARTITIONING BASED ON REDUCTION OF $\text{FeO}$ IN SLAG

As discussed in Section E.4 of Appendix E, an indication of contaminant partitioning between the melt and the slag can be obtained by calculating the free energy change for the reaction



where M is the pure component rather than the solute dissolved in the melt and  $\text{FeO}$  and  $\text{M}_x\text{O}_y$  are slag components. The standard free energies of reaction of various contaminants with  $\text{FeO}$  at 1,873 K, a typical temperature for the production of carbon steel in an EAF, were presented in Table E-2. Recalculation of these values for a temperature of 1,573 K, which is typical for cast iron production, indicates no substantive changes from the previous conclusions regarding which elements are expected to concentrate in the slag and which are expected to concentrate in the melt. The assumed 300 K temperature difference between steel melting and cast iron melting produces small changes in the free energies based on Equation F-1, but no significant shifts in the expected equilibria. The free energies of reaction at 1,573 K are listed in Table F-3.

### F.4 ADJUSTMENTS TO HENRY'S LAW FOR DILUTE SOLUTIONS

Partition ratios presented in Table E-1 for carbon steel were also recalculated for a furnace temperature of 1,573 K. While slight changes in partitioning ratios were obtained at the lower temperature, no significant shifts in equilibria resulted. An example is the comparable partition ratios for cobalt and uranium, which are shown in Table F-4.

Calculations of partition ratios at 1,573 K are summarized in Table F-5. Values of  $\gamma^\circ$  were calculated using temperature-dependent values of the free energy change for transference of the

pure substance to a dilute solution in liquid iron. All values were obtained from Sigworth and Elliot (1974) except cerium, which was taken from JSPS 1988.

Table F-3. Standard Free Energy of Reaction of Various Contaminants with FeO at 1,573 K

Element	Oxide	$\Delta F^\circ$ (kcal)	Comments
Ac <sub>(l)</sub>	Ac <sub>2</sub> O <sub>3</sub>	-121	Ac should partition to slag
Am <sub>(l)</sub>	Am <sub>2</sub> O <sub>3</sub>	-105	Am should partition to slag
Ba <sub>(l)</sub>	BaO	-59.6	Ba should partition to slag
Cs <sub>(l)</sub>	Cs <sub>2</sub> O		Cs <sub>2</sub> O unstable at 1,573 K, Cs should vaporize from melt, some Cs may react with slag components
Np <sub>(l)</sub>	NpO <sub>2</sub>	-104	Np should partition to slag
Pa <sub>(l)</sub>	PaO <sub>2</sub>	-100	Pa should partition to slag
Pu <sub>(l)</sub>	Pu <sub>2</sub> O <sub>3</sub>	-89.1	Pu should partition to slag
Ra <sub>(g)</sub>	RaO	-55.0	Ra should partition to slag
Ru <sub>(s)</sub>	RuO <sub>4</sub>		Ru should remain in melt
Sb <sub>(g)</sub>	Sb <sub>2</sub> O <sub>3</sub>		Sb will not react with FeO, some may vaporize from melt
Sr <sub>(g)</sub>	SrO	-65.8	Sr should partition to slag, but low boiling point could cause some vaporization
Tc <sub>(s)</sub>	TcO <sub>2</sub>		Tc will not react with FeO, should remain in melt
Th <sub>(s)</sub>	ThO <sub>2</sub>	-147	Th should partition to slag
Y <sub>(l)</sub>	Y <sub>2</sub> O <sub>3</sub>	-104	Y should partition to slag
Zn <sub>(g)</sub>	ZnO		Zn will not react with FeO, Zn should vaporize from melt

Table F-4. Partition Ratios of Two Elements at Typical Iron- and Steel-Making Temperatures

Element	Partition Ratio ( $N_{MO}/wt\% M$ )	
	1,573 K	1,873 K
Co	1.0e-4	4.8e-5
U	1.4e+8	8.9e+7

Table F-5. Partition Ratios at 1,573 K for Various Elements Dissolved in Iron and Slag

M	Oxide	$\gamma^{\circ}_M$	$\Delta F^{\circ}_{f,MO}$ (kcal/mole) <sup>a</sup>	Partition Ratio ( $N_{MO}/wt\%M$ )
Ag <sub>(l)</sub>	Ag <sub>2</sub> O	546	+16.5	1.06e-03 <sup>b,c</sup>
Al <sub>(l)</sub>	Al <sub>2</sub> O <sub>3</sub>	0.013	-280	2.63e+05 <sup>b</sup>
Ca <sub>(g)</sub>	CaO	1330	-118	1.15e+10
Ce <sub>(l)</sub>	Ce <sub>2</sub> O <sub>3</sub>	0.26	-302	1.79e+07 <sup>b</sup>
Co <sub>(l)</sub>	CoO	1.08	-25.0	1.00e-04
Cr <sub>(s)</sub>	Cr <sub>2</sub> O <sub>3</sub>	1.45	-111	1.86e-03 <sup>b</sup>
Cu <sub>(l)</sub>	Cu <sub>2</sub> O	12.9	-14.0	2.56e-03 <sup>b</sup>
Mn <sub>(l)</sub>	MnO	1.36	-64.3	5.24e+00
Mo <sub>(s)</sub>	MoO <sub>3</sub>	2.60	-95.3	3.49e-06
Nb <sub>(s)</sub>	Nb <sub>2</sub> O <sub>5</sub>	1.79	-298	1.22e+05 <sup>b</sup>
Ni <sub>(l)</sub>	NiO	0.51	-25.1	4.98e-05
Pb <sub>(l)</sub>	PbO	11900	-17.8	4.56e-02
Si <sub>(l)</sub>	SiO <sub>2</sub>	2.7e-4	-143	4.00e+01
Sn <sub>(l)</sub>	SnO <sub>2</sub>	3.44	-61.7	3.70e-05
Ti <sub>(s)</sub>	TiO <sub>2</sub>	0.035	-159	2.22e+05
U <sub>(l)</sub>	UO <sub>2</sub>	0.014	-193	1.44e+08
V <sub>(s)</sub>	V <sub>2</sub> O <sub>5</sub>	0.078	-228	9.93e+00 <sup>b</sup>
W <sub>(s)</sub>	WO <sub>3</sub>	1.73	-110	6.56e-05
Zr <sub>(s)</sub>	ZrO <sub>2</sub>	0.029	-191	4.52e+08

<sup>a</sup>  $\Delta F^{\circ}_{f,FeO} = -38.1$  kcal/mole

<sup>b</sup> PR =  $N^{1/2}/wt\% M$

<sup>c</sup> Ag will not react with FeO, Ag<sub>2</sub>O unstable at 1,573K

## F.5 OBSERVED PARTITIONING DURING METAL MELTING

### F.5.1 General Observations

Because of concerns that tramp elements might be accumulating in cast irons from contaminants in steel scrap and affecting casting behavior, the U.S. Bureau of Mines conducted an extensive study over a period of more than five years to evaluate the impurities in cast iron (Natziger et al. 1990). While this study does not specifically address partitioning, the results can provide confirmation of inferred partitioning. Samples were obtained from 28 ductile iron foundries and

52 gray iron foundries at various times over the course of the study. The distribution of foundries by geographical location, furnace type and product is shown in Table F-6.

Table F-6. Distribution of Foundries in Bureau of Mines Tramp Element Study

Zone	Ductile Iron						Gray Iron					
	Furnace Type			Size <sup>a</sup>			Furnace Type			Size <sup>a</sup>		
	Cupola	Electric	Induction	A	B	C	Cupola	Electric	Induction	A	B	C
Northeast	1	0	2	1	1	1	6	0	2	3	5	0
Great Lakes	5	0	2	1	2	4	12	0	2	4	7	3
Southeast	1	1	3	3	1	1	4	0	3	3	2	2
Upper Midwest	4	1	3	0	8	0	11	1	4	0	12	4
West	1	0	4	5	0	0	3	1	3	5	1	1

Source: Natziger et al. 1990

<sup>a</sup> A: < 1,000 tons per month; B: 1,000 to 8,000 tons per month; C: >8,000 tons per month

With limited exceptions, cerium, niobium, lead, and antimony were not found at the limits of detection (wt%) listed below for the 23 calendar quarters over which sampling was conducted:

- Ce ..... 0.02 - 0.1
- Nb ..... 0.01 - 0.05
- Pb ..... 0.005 - 0.2
- Sb ..... 0.02 - 0.1

Lead levels above the lower detection limit were observed in four quarters, as shown in Table F-7.

Table F-7. Lead Levels at Two Different Types of Foundries

Quarter	Pb Above Detection Limits (wt%)	
	Ductile Iron	Gray Iron
1	0.005-0.007	< 0.005-0.007
2	< 0.005-0.008	< 0.005-0.010
3		< 0.005-0.006
20		< 0.005-0.007

Source: Natziger et al. 1990

Average analyses for other elements of interest are included in Table F-8.

Table F-8. Average Concentrations of Tramp Elements in Cast Iron (wt%)

Zone	Ductile Iron					Gray Iron				
	Co	Mn	Mo	Ni	Zn	Co	Mn	Mo	Ni	Zn
Northeast	0.008	0.378	0.020	0.067	0.003	0.009	0.726	0.025	0.073	0.002
Great Lakes	0.007	0.405	0.022	0.117	0.003	0.010	0.703	0.051	0.192	0.002
Southeast	0.009	0.453	0.017	0.171	0.004	0.010	0.675	0.030	0.142	0.003
Upper Midwest	0.008	0.409	0.024	0.257	0.002	0.009	0.701	0.040	0.107	0.002
West	0.012	0.415	0.025	0.186	0.005	0.009	0.670	0.040	0.086	0.002

Source: Natziger et al. 1990

### F.5.2 Antimony

Thermodynamic calculations based on Equation F-1 indicate that antimony will not partition to the slag. Experimental work by Kalcioglu and Lynch (1991) showed that when antimony is added to carbon-saturated iron at 1,723 K and allowed to react with an acidic slag (basicity ratio = 0.666), the resulting partition ratios were those listed in Table F-9.

Table F-9. Distribution of Antimony Between Slag and Metal

[wt%Sb] <sup>a</sup>	$L_{Sb}$ <sup>b</sup>
0.45	0.067
0.87	0.022
1.03	0.020
1.06	0.018

<sup>a</sup> [wt%Sb] = concentration in metal

<sup>b</sup>  $L_{Sb}$  = (wt%Sb)/[wt%Sb]  
 (wt%Sb) = concentration in slag

Based on these values for  $L_{Sb}$  and an assumed slag-to-metal mass ratio of 0.05, the quantities of antimony in the slag are insignificant (i.e., <1%). Antimony recoveries ranged from 47% to 71% for these four tests, the losses being presumably due to vaporization.

Nassaralla and Turkdogan (1993) cite the following equation for the activity of antimony in carbon-saturated iron:

$$\log \gamma_{\text{Sb}}^{\circ} = -\frac{6623}{T} + 5$$

This yields a value for  $\gamma^{\circ}$  of 6.2 at 1,573 K, which, when combined into the Henry's Law relationship, indicates that the partition ratio,  $\frac{(N_{\text{Sb}_2\text{O}_3})^{1/2}}{[\text{wt}\% \text{ Sb}]}$ , is  $2.6 \times 10^{-5}$ , supporting the view that antimony partitions strongly to the melt. Although, as noted in Section F.5.1, no antimony was found in cast iron samples at the lower limit of detection (0.02 - 0.1 wt%), this does not necessarily vitiate the thermodynamic partitioning argument. Antimony may not be present in the feed materials at the detection limit. Although some antimony may vaporize from the melt, insufficient evidence is available to quantify this possibility. To avoid possibly underestimating exposures to cast iron products potentially contaminated with antimony, antimony is assumed to remain in the melt.

### F.5.3 Carbon

As was noted in Sections F.2.1 - F.2.3, carbon is added to the furnace charge to achieve the levels desired in the finished product (e.g. 1.8% to 4.0% C). During the melting process, some of the carbon in the scrap steel may be oxidized and removed from the system as CO; however, there is a net addition of carbon to the melt, rather than a net removal. Since it is impossible to predict how much carbon is removed from the scrap steel and later replaced with carbon from other charge materials, it is conservatively assumed that all the carbon in the scrap remains in the cast iron.

### F.5.4 Cerium

Cerium is sometimes used as an inoculant in ductile irons (Baldwin 1980); consequently, small amounts must remain in the melt, in spite of the fact that thermodynamic calculations suggest that cerium partitions strongly to the slag. In addition, as noted in Section F.5.1, cerium was not found in cast iron at the limits of detection in samples from 28 ductile iron foundries. Given this conflicting information, the most likely situation is that minute amounts of cerium will remain in the cast iron. However, no evidence has been uncovered which suggest that the amount of cerium remaining in the melt is greater than 0.5% of the total.<sup>3</sup>

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<sup>3</sup> Partition ratios in the present analysis are calculated to the nearest 1%. Thus, any partition ratio less than 0.5% is assigned a value of zero.

#### F.5.5 Cesium

Cesium is expected to partition to the slag and to accumulate in the baghouse dust. None is expected to remain in the melt (Harvey 1990).

#### F.5.6 Iron

Some iron is expected to be oxidized and to transfer to the slag. However, no detailed composition data have been located in this study to permit quantification of this expected partitioning. Therefore, it is conservatively assumed that no iron partitions to the slag.

#### F.5.7 Lead

Based on thermodynamic equilibrium calculations, lead is expected to remain in the melt. However, lead has very limited solubility in liquid iron. Furthermore, it has a vapor pressure of 0.01 atm at 1,408 K (Darken and Gurry 1953) and 0.05 atm at 1,462 K (Perry and Green 1984). At the limits of detection, lead is seldom found in cast iron (see Section F.5.1).

Lead has been detected in leachates from baghouse dust collected by cupola emission control systems. Leachate levels based on the EP toxicity test ranged from about 10 to about 220 mg/L (Kunes et al. 1990). Since it is not possible to quantitatively relate these leachate results to contaminant levels in the dust, one can only reach the qualitative conclusion that some lead vaporizes from the cast iron melt and is collected in the baghouse.

The combined evidence indicates that, for the purposes of the present analysis, lead can be assumed to completely vaporize from the melt.

#### F.5.8 Manganese

Based on thermodynamic calculations which assume that  $\gamma_{\text{Mn}}^{\circ} = 2.6$ , the partition ratio of manganese between slag and iron is calculated to be about 5 at 1,573 K (see Table F-5), which suggests that significant amounts of manganese will be present in both the slag and the melt. Meraikib (1993) determined that during steelmaking, the distribution of manganese between the slag and the melt could be described by the equation

$$\eta_{\text{Mn}} = \frac{(\text{Mn})}{[\text{Mn}]}$$

$$= a_{[\text{O}]} f_{[\text{Mn}]} \exp\left(\frac{27530}{T} - 0.0629 B - 7.3952\right)$$

(Mn) = concentration of manganese in slag (wt%)

[Mn] = concentration of manganese in melt (wt%)

$a_{[\text{O}]}$  = activity of oxygen in melt

$f_{[\text{Mn}]}$  = activity coefficient for [Mn]

T = absolute temperature (K)

B = slag basicity

Although there are risks in extrapolating this equation to cast iron melting, the calculation was undertaken in the absence of better information. Partition ratios at two different partial pressures of CO were estimated, assuming  $T = 1,573 \text{ K}$ ,  $B = 0.63$ ,  $f_{[\text{Mn}]} = 0.95$ , and 130 lb of slag generated per ton of metal melted. These values are listed in Table F-10.

Table F-10. Partition Ratios of Manganese at Different Partial Pressures of CO

$P_{\text{CO}}$ (atm)	$\eta_{\text{Mn}}$	Partition Ratio (see text) (mass in slag/mass in metal)
1	0.45	0.03
0.1	0.045	0.003

Note: The oxygen activity is calculated using free energy values for C and O dissolved in iron (JSPS 1988) and the CO free energy of formation given by Glassner (1957). The calculated values are in close agreement with information presented by Engh (1993, p. 67).

### F.5.9 Niobium

On the basis of thermodynamic calculations, niobium is expected to partition primarily to the slag. However, according to Harvey (1990), niobium can be retained in steel under reducing conditions. The expected reaction is



where the elements on the left side of the equation are melt constituents and the compound on the right is a slag constituent. The equilibrium constant for the reaction is

$$K_1 = \frac{a_{\text{FeO} \cdot \text{Nb}_2\text{O}_5}}{a_{\text{Fe}} a_{\text{Nb}}^2 a_{\text{O}}^6} = 2.4 \cdot 10^{10} \quad (T = 1,873\text{K})$$

Assuming that  $\frac{a_{\text{FeO} \cdot \text{Nb}_2\text{O}_5}}{a_{\text{Fe}}} = 1$ , values of  $a_{\text{Nb}}$  corresponding to two assumed values of  $a_{\text{O}}$  were calculated, as listed below:

$a_{\text{O}}$	$a_{\text{Nb}}$
1	6.5e-6
0.01	6.5

The value of  $K_{1573}$ , the equilibrium constant at 1,573 K, is not available; however, based on the values of the free energies of formation of  $\text{Nb}_2\text{O}_5$  at 1,573 K and 1,873 K, it is expected that  $K_{1573} > K_{1873}$ . Thus, a highly reducing environment ( $a_{\text{O}} \ll 1$ ) would be required to retain niobium in the melt at the lower temperature.

As noted in Section F.5.1, niobium is not detected in cast iron at the detection limit, which indicates that either there are no significant quantities of niobium in steel scrap or the typical melting conditions are not sufficiently reducing to cause niobium to be retained in the melt.

#### F.5.10 Zinc

Under steelmaking conditions, zinc is expected, from a free energy perspective, not to partition to the slag and, because of its high vapor pressure, to vaporize from the melt to a large extent. Cast iron melting temperatures, though lower, are still well above the normal boiling point of zinc (1,180 K).

Based on information presented by Perrot et al. (1992), the solubility of zinc at 1,573 K is expected to be about 140 ppm when the partial pressure of zinc is  $10^{-2}$  atm. Silicon in the cast iron will tend to increase the zinc solubility while manganese will have the opposite effect. As noted in Section F.5.1, from 20 to 50 ppm of zinc are typically found in cast iron, which suggests that it is unrealistic to assume that 100% of the zinc volatilizes and collects in the baghouse.

Assume, for example, that a furnace charge contains 45% steel scrap and 55% cast iron scrap, and that both the cast iron scrap and the product contains 30 ppm Zn, as listed in Table F-8. If the steel scrap contains less than 0.67 wt% Zn, then 1% or more of the zinc would remain in the melt (see Note 3) (Koros 1994).

According to Koros (1994), typical galvanized scrap contains about 2% Zn. The same author reported that, in 1992, 35% of the scrap classified as No. 1 bundles and busheling is galvanized steel. Other grades of scrap likely to contain significant quantities of galvanized steel include shredded scrap and No. 2 bundles (Fenton 1996). For 1993, No. 1 bundles, No. 1 busheling, shredded, and No. 2 bundles accounted for 46% of the carbon steel scrap used in iron foundries (Bureau of Mines 1995). Using the above information, it can be estimated that about 2% of the zinc will remain in the cast iron and the balance will be transferred to the baghouse dust, based on the following calculation:

$$P_{Fe}^{Zn} = \frac{C_{Fe}^{Zn}}{f_{Fe}^{Fe'} C_{Fe'}^{Zn} + f_{Fe}^s f_s^{g'} f_{g'}^g C_g^{Zn}}$$

$$P_{Fe}^{Zn} = \text{partition fraction of zinc in cast iron} \\ = 0.0205$$

$$C_{Fe}^{Zn} = \text{mass fraction of zinc in cast iron product} \\ = 3 \times 10^{-5}$$

$$f_{Fe}^{Fe'} = \text{mass ratio of cast iron scrap : cast iron product} \\ = 0.55$$

$$C_{Fe'}^{Zn} = \text{mass fraction of zinc in cast iron scrap} \\ = 3 \times 10^{-5}$$

$$f_{Fe}^s = \text{mass ratio of steel scrap : cast iron product} \\ = 0.45$$

$$f_s^{g'} = \text{fraction of galvanized-steel-bearing scrap sources in steel scrap} \\ = 0.46$$

$$f_s^{g'} = \text{fraction of galvanized steel in galvanized-steel-bearing scrap sources} \\ = 0.35$$

$$C_g^{Zn} = \text{mass fraction of zinc in galvanized steel} \\ = 0.02$$

## F.6 PARTITIONING SUMMARY

### F.6.1 Elements Which Partition to the Melt

It is assumed that 1% of the total melt will be transported from the furnace and collected in the baghouse. This is approximately the geometric mean of the values for two types of foundries listed in Table F-2 and is consistent with the values cited in U.S. EPA 1995 (see Section F.2). Based on thermodynamic equilibria, the following elements are expected to partition 99% to the melt and 1% to the baghouse dust: cobalt, molybdenum, nickel, ruthenium, and technetium.

Free energy calculations also suggest that silver partitions to the melt but, for EAF melting of carbon steel, this information was tempered by the facts that silver has a significant vapor pressure at steelmaking temperatures ( $10^{-2}$  atm at 1,816 K) and some work on stainless steel melting done at Studsvik (Menon et al. 1990) had shown silver in the baghouse dust. However, the vapor pressure of silver is at least an order of magnitude lower at temperatures used in cast iron melting (e.g.,  $10^{-3}$  atm at 1,607 K)(Darken and Gurry 1953). Consequently, in cast iron, silver is assumed to partition 99% to the melt and 1% to the baghouse dust.

Although there is reason to suspect that some niobium might be found in the melt under highly reducing conditions, no evidence was uncovered to support that supposition.

For reasons discussed in Section F.3.3 above, carbon and antimony are expected to remain in the melt except for small quantities contained in dust transferred to the baghouse (i.e., 1%).

Manganese is predicted to remain primarily in the melt. It is expected that no more than about 2% of the manganese will partition to the slag.

Most of the zinc is expected to volatilize and be collected in the baghouse. Only about 2% is assumed to remain in the melt.

Table F-11 lists the partition ratios of elements which are expected to show significant (i.e., at least 1%) partitioning to the melt.

## F.6.2 Elements Which Partition to Slag

For those elements which are strong oxide formers and are expected to partition to the slag, the assumption is made here that 5% of the slag will be transported to the baghouse as dust. This is the same assumption as made for melting carbon steel in electric arc furnaces. Based on this assumption, thermodynamic equilibrium calculations at 1,573 K and chemical analogies, the following elements are expected to partition 95% to the slag and 5% to the baghouse dust: Ac, Am, Ce, Cm<sup>4</sup>, Eu<sup>4</sup>, Nb, Np, Pa, Pm<sup>4</sup>, Pu, Ra, Sr, Th, and U.

Table F-11. Proposed Partitioning of Metals Which Remain in the Melt

Element	Distribution (%)		
	Melt	Slag	Baghouse
Ag	99		1
C	99		1
Co	99		1
Fe	99		1
Mn	97	2	1
Mo	99		1
Ni	99		1
Ru	99		1
Sb	99		1
Tc	99		1
Zn	2		98

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<sup>4</sup> Since thermodynamic data were not available for these elements, partitioning was assumed to be analogous to similar elements in the rare-earth and actinide series in the periodic table.

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